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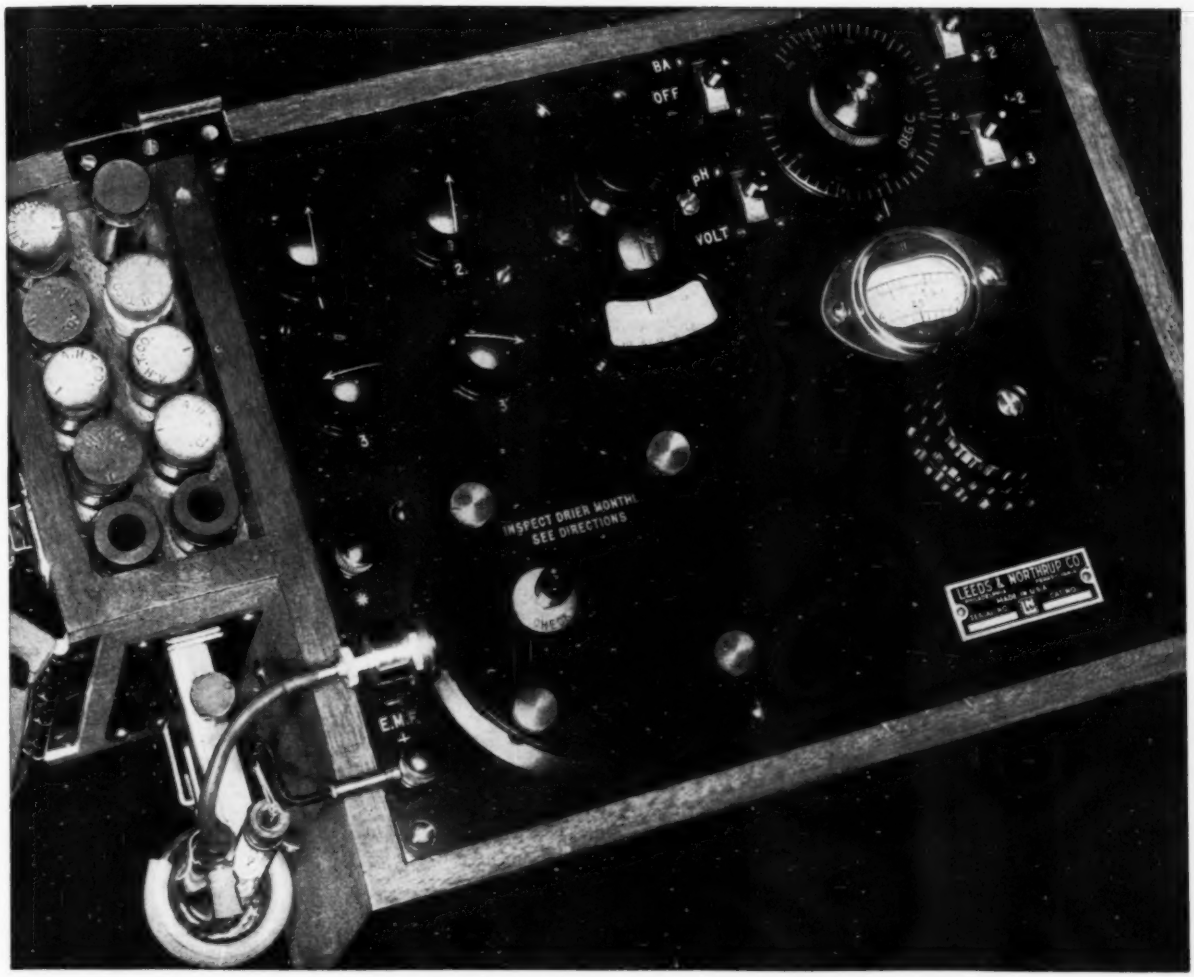

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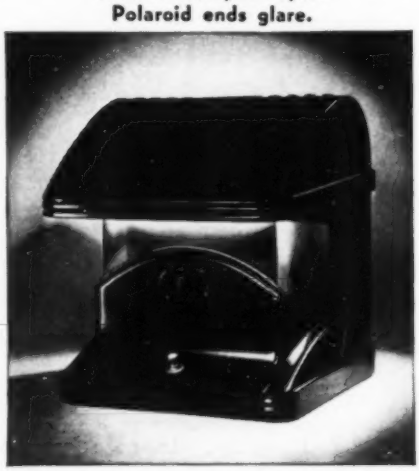

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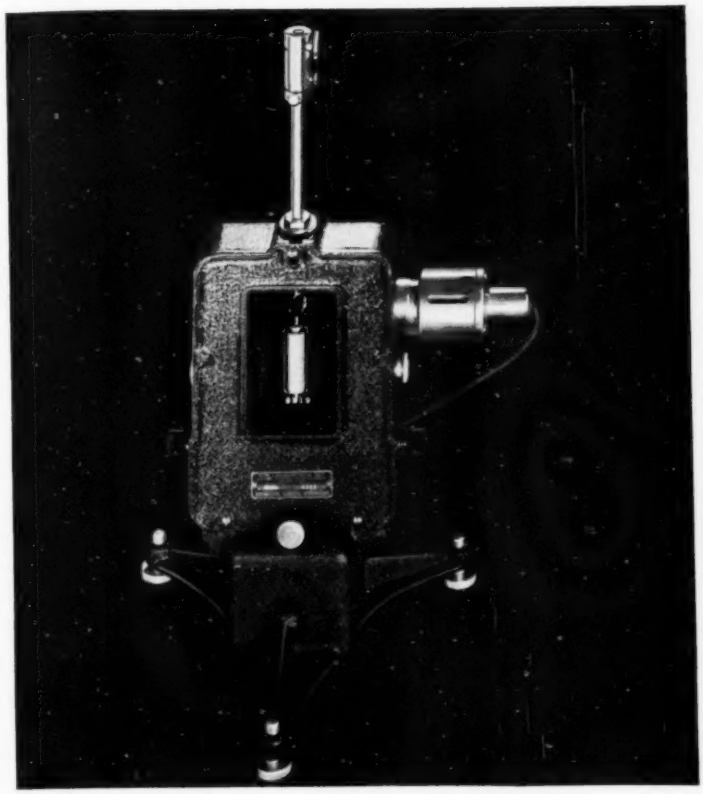

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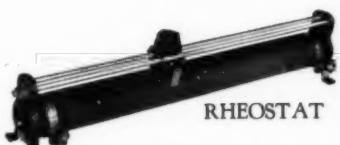

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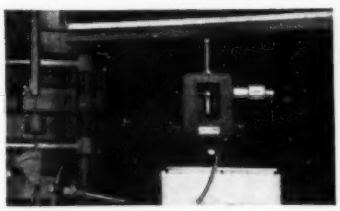

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Innovations in Instruments (continued)

chromatic Film. In addition to the Type B film for studio use, a daylight type is expected to be available later in a similar range of sizes.

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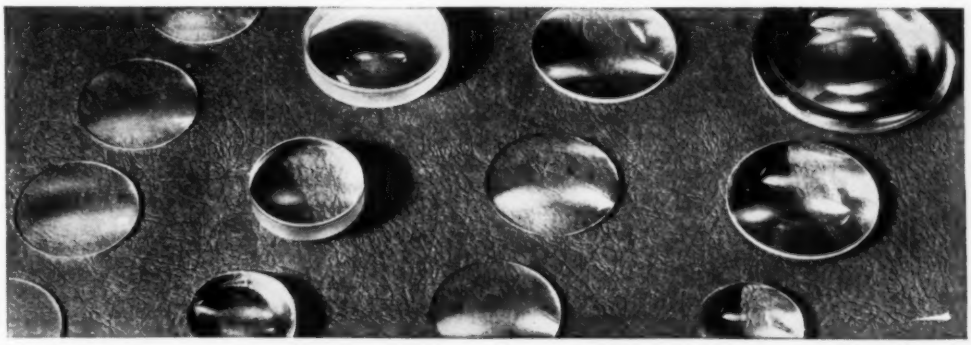
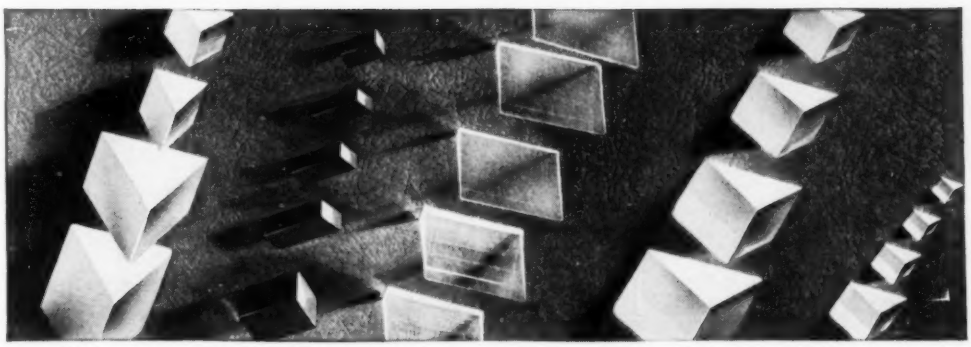
New *p*H Slide Comparator

A new slide comparator for the colorimetric determination of *p*H, chlorine and phosphates has been developed by W. A. Taylor & Company, 872 Linden Avenue, Baltimore, Maryland. The new outfit is molded entirely from plastic. All *p*H, chlorine and phosphate values, as well as the indicator names, are engraved in white directly on the plastic slides. Improved catches are used to hold the top on the base and all metal parts are rustproof. The whole outfit, including the slide is 10 in. long, 2⅛ in. wide and 4 in. high and weighs only 1½ lb.

The new comparator consists of a slide and a base. Each slide contains 9 color standards alternating with ampoules of distilled water. All color standards are guaranteed by the manufacturer to maintain their accuracy for a period of 5 years. The base contains 2 vials of indicator solution, with 0.5-cc pipettes, 5 5-cc test tubes, and a piece of etched glass in a special compartment. Determinations are made by filling three of the test tubes with the test sample, adding 0.5 cc of indicator solution to the middle one, placing the slide on the base and moving it back and forth until the test sample matches one of the color stand ards. The *p*H, chlorine or phosphate value is then read off directly from the values on the slide. One base can be used with any number of color standard slides.





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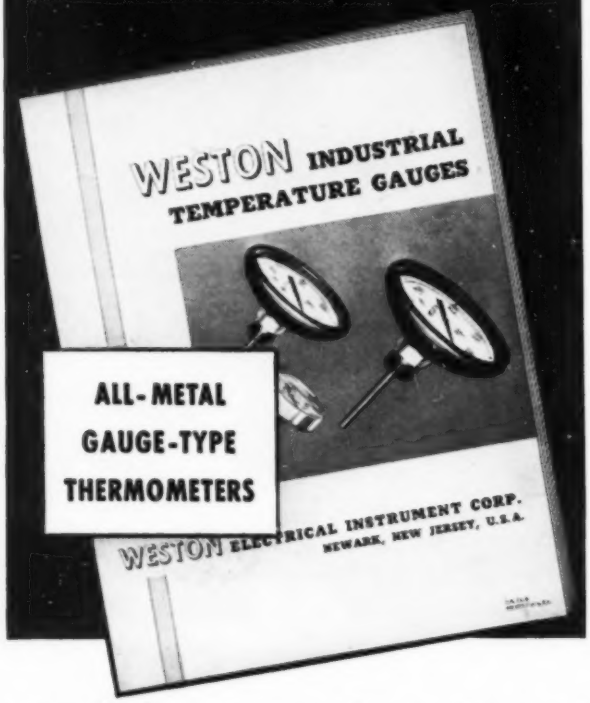

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Journal of Applied Physics

Volume 9 December, 1938 Number 12

Penetration of Oil Sprays

By P. H. Schweitzer

Professor of Engineering Research, The Pennsylvania State College, State College, Pennsylvania

Penetration of the Spray Tip

Instead of using high speed photography as N.A.C.A.,[1] Sass,[2] and Holfelder,[3] the penetration of the spray tip in consecutive small time intervals was determined by a sensitive electric contact upon which the spray impinged. Fig. 1 is a photograph of the pressure chamber with the injection mechanism producing single injections and Fig. 2 shows the schematic arrangement used in the tip penetration tests. In series with the spray contact was a timed contact, the phase of which could be changed by turning a disk on the shaft which actuated the injection valve. When both the spray contact and the timed contact were closed simultaneously, the neon lamp flashed. From this the time when the spray reached the spray contact was determined. Fig. 3 was obtained in this manner. The penetration of the spray tip grows fast in the beginning but slows down later. The curves for tip velocities, which are obtained by graphical differentiation, flatten out quickly and the effect of the injection pressure diminishes.

The factors that have considerable effect on spray tip penetration are: injection pressure, chamber pressure, orifice size, orifice shape and oil viscosity. Dimensional analysis[4] served to establish certain relations, by which the effect of most important variables on spray tip penetration can be calculated.

The effect of the injection pressure can be expressed by the formula

$$s=f(tp^{\frac{1}{2}}), \tag{1}$$

where s is penetration (inches), t is time (milliseconds), p is oil pressure (lb. per sq. in.). According to this equation the penetration is unchanged if $tp^{\frac{1}{2}}$ is unchanged. From Fig. 3 the spray tip of a 4000 lb. per sq. in. spray reaches 8 in. in 12 milliseconds. How long does it take a 1000 lb. per sq. in. spray to get that far? Since $tp^{\frac{1}{2}}$ is the same in both cases, the low pressure spray will need $12(4000/1000)^{\frac{1}{2}}=24$ milliseconds to traverse the 8 in. distance. This closely agrees with the reading on Fig. 3, which was obtained experimentally. The significance of Eq. (1) is that if the penetration curve is known for one injection pressure, it can be calculated for any other injection pressure.

The effect of the orifice diameter on penetration can be expressed by the formula

$$s/d=f(t/d), \tag{2}$$

where d is the orifice diameter. This enables us to calculate tip penetration for any orifice diameter from the data for a similar nozzle of another orifice diameter. Eq. (2) does not furnish an explicit formula, but with the s *vs.* t curve known for one orifice diameter, the s/d *vs.* t/d curve can be plotted, which will be the same for

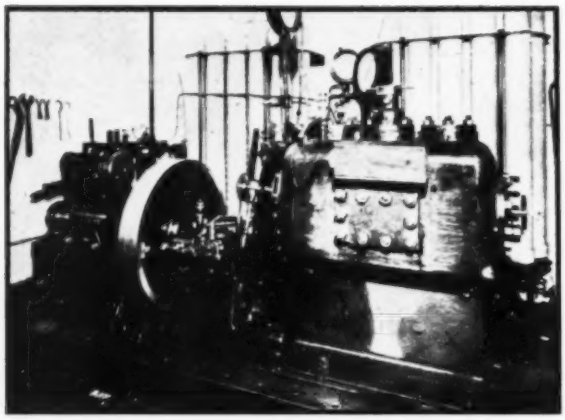


FIG. 1. Pressure chamber (closed) and injection mechanism.

any orifice diameter. Therefore a new s *vs.* t curve can be plotted for another orifice diameter.

The effect of chamber pressure or chamber air density ρ_a can be expressed by the formula

$$s(1+\rho_a)=f(t\rho_a), \tag{3}$$

which again makes it possible to draw a tip penetration curve $s=f(t)$ for any chamber air density if it is known for one chamber air density.

The formulas (1), (2) and (3) can be combined in a single formula

$$s/d(1+\rho_a)=f(t/d\rho_a p^{\frac{1}{2}}). \tag{4}$$

Fig. 4 represents such a plot for an oil of 13.5 centistokes kinematic viscosity and 0.908 specific gravity, showing that in spite of widely varying injection pressures, chamber air densities and

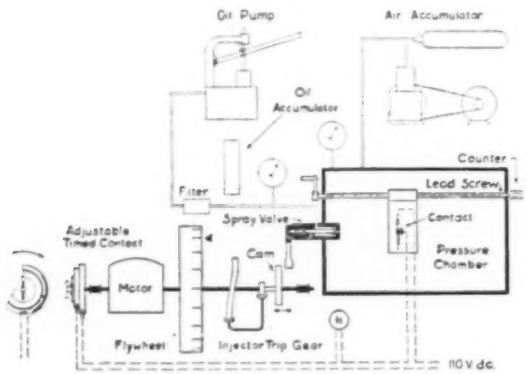
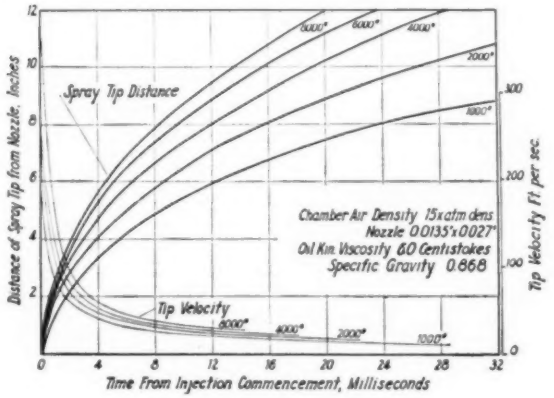


FIG. 2. Schematic arrangement of pressure chamber and injection mechanism.

orifice diameters, all points fall substantially on the same line. The dimensional formula is also supported by data of Sass,[2] Gellales,[5] Beardsley[6] and Holfelder.[3]

Finally, it may be stated that tip penetration can be conveniently controlled by injection pressure and orifice diameter. In this way penetration distance can be increased or decreased by 50 percent or more. Chamber air density has a pronounced effect on tip penetration at low air densities but in the Diesel range its effect is insignificant.

The motion of the spray *tip* as described above has frequently been taken as the motion of the sprayed liquid itself. The assumption is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Tip Velocity Ft per sec.
Time From Injection Commencement, Milliseconds

FIG. 3. Spray tip penetration in air of 15 times atmospheric density.

sometimes made,[2] that the spray tip represents the motion of the leading droplets which have the highest velocity and that the other droplets are trailing the leaders with somewhat lower velocities. This assumption would be correct if the leading droplets would remain leaders any length of time. This is, no doubt, the case in vacuum but not in dense air, nor even in atmospheric air. With air resistance present, the droplet that leads the spray at one instant is stopped the next by air resistance. Other droplets coming from behind overtake the former leader only to be stopped very shortly afterward. At the beginning of their flight the particles move with a velocity greater than that of the spray tip. The spray can be visualized as boring a hole in the air and the *tip velocity is nothing but the rate at which the hole in the air grows.*

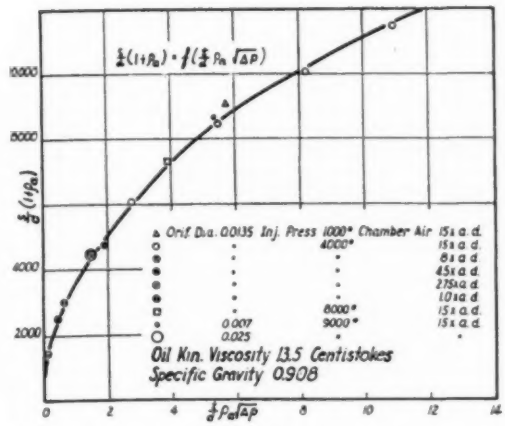

Orif Dia. 0.0135 Inj. Press 1000* Chamber Air 15 a. d.
4000* 15 a. d.
8 a. d.
4.5 a. d.
2.75 a. d.
1.0 a. d.
8000* 15 a. d.
0.007 9000* 15 a. d.
0.025
Oil Kin. Viscosity 13.5 Centistokes
Specific Gravity 0.908

FIG. 4. Plot of $(s/d)(1+\rho_a)$ *vs.* $(t/d)\rho_a p^{\frac{1}{2}}$. In spite of widely varying injection pressures, chamber air densities, and orifice diameters, all points fall substantially on the same line. Units: t in seconds, ρ_a in units of atmospheric density, p in pound per square inch, s in inches.

More than anything else, it is the motion of the individual droplet that the engine designer is interested in. He endeavors to create conditions such that the greatest number of particles burn in contact with sufficient air and wants to know where the oil droplets are in consecutive time intervals. A study of the spray tip alone will not furnish this information. The curves in Fig. 3 tell us where the farthest advanced droplets are at a certain moment but not where the rest of the droplets are at that time or at any other time. The true story would be obtained by tagging and observing the individual droplets. This course is fraught with difficulties. The next best thing is to ascertain the fate of the average droplet. This has been done to a certain degree by measuring mass effects.

The ballistic pendulum determined the mean velocity of the oil droplets by measuring the effect of their impact on a plate. The tipping cut determined what portion of the total spray reached a certain distance from the nozzle.

BALLISTIC PENDULUM

The ballistic pendulum takes its name from its use for measuring the velocities of rifle bullets. In its simplest application the bullet of mass m impinges with velocity c on a freely suspended inelastic body of mass M. From the equality of momenta

$$m\times c+M\times 0=(M+m)u. \qquad (5)$$

By knowing u (from the deflection of the pendulum), m and M the velocity c can be calculated.

A number of spray velocity determinations were made with a ballistic pendulum enclosed in the pressure chamber on the assumption that the impinging mass of the entrained air that also impinges on the mass M can be neglected. This assumption proved to be untenable. It became evident that the ballistic pendulum cannot be expected to give useful results unless the impact of the air is eliminated or corrected for. The method finally adopted was found by accident.

During some earlier experiments a shield plate with a $1\frac{1}{4}''$ hole was placed closely in front of the pendulum disk in the hope that such a shield would prevent the greater part of the air from impinging upon the pendulum and yet would permit almost all of the oil to pass freely through the opening. This shield was found to act in a very unexpected manner. It not only prevented the peripheral air from impinging on the pendulum plate but caused the air passing through the hole of the shield disk to exert a *pull* on the pendulum disk instead of a push. This is similar to the fairly well-known observation that blowing through a thread spool will suck a name card to its face

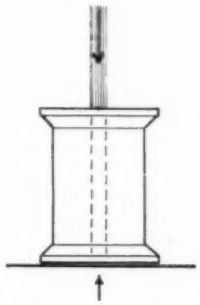


FIG. 5. Blowing through a thread spool holds a card to its face.

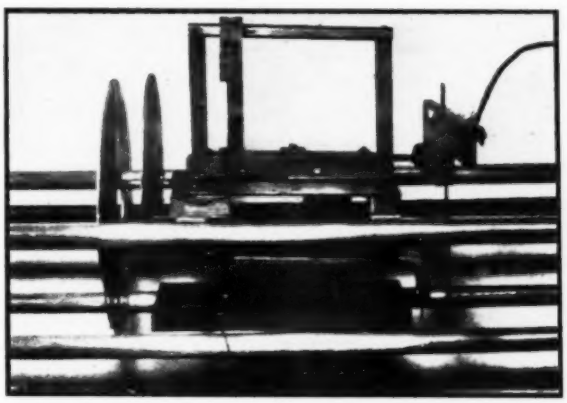


FIG. 6. Photograph of ballistic pendulum.

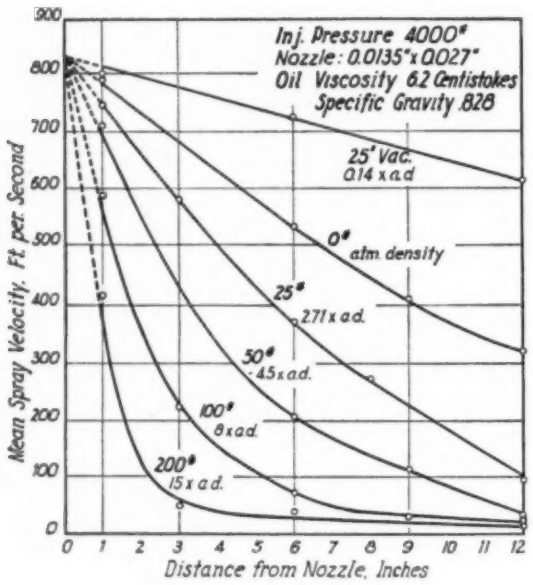


FIG. 7. Spray velocities. Effect of chamber air density. These curves were obtained by means of a "shielded" ballistic pendulum and represent the "true" mean velocities of the oil globules.

instead of pushing it off, see Fig. 5. The explanation in both cases is that the deflected air expands and exerts a Venturi-like aspirator effect on the plate. The following facts were established:

1. If the clearance distance between shield disk and target disk is small, the air exerts a pull on the target disk; if the clearance is large, it exerts a push.

2. A position can always be found for the shield disk where neither a push nor a pull is discernible. With "neutral" shield clearance the air stream exerts zero force on the target disk.

3. The neutral clearance is practically independent of the air velocity and quantity.

These findings indicated that a shielded ballistic pendulum might be used for the determination of the true spray velocities. In order to determine whether or not such a course was safe, a more detailed investigation was made which confirmed the belief that the shielded ballistic pendulum records the spray velocities in a reliable manner. The tests to be described were made on that basis.

The pressure chamber and injection mechanism were unchanged but the sensitive contact was replaced with a shielded ballistic pendulum as shown on Fig. 6. The deflection of the ballistic pendulum, enclosed in the pressure chamber was registered electrically in distances 1, 3, 6, 9, and 12 inches from the nozzle.

Figure 7 shows the results with a light Diesel oil injected under 4000 lb. per sq. in. pressure into air of varying density. It will be noticed that while the spray velocity is still appreciable at 12 in. distance in atmospheric air, the velocity almost vanishes at 3 in. from the nozzle in air of 15 times atmospheric density (corresponding to average compression in a Diesel engine). Fig. 8 shows that higher injection pressures produce higher issue velocities but the deceleration is so much more rapid with the high pressure spray that after $2\frac{1}{2}$ in. travel the velocities are substantially equal.

Figure 9 shows the penetration of the "average globule" plotted against time. The curves, which were obtained by graphical conversion from the mean velocity curves, refer to the standard conditions indicated except for one changed factor which is marked on the curve. The unmarked curve corresponds to standard conditions throughout.

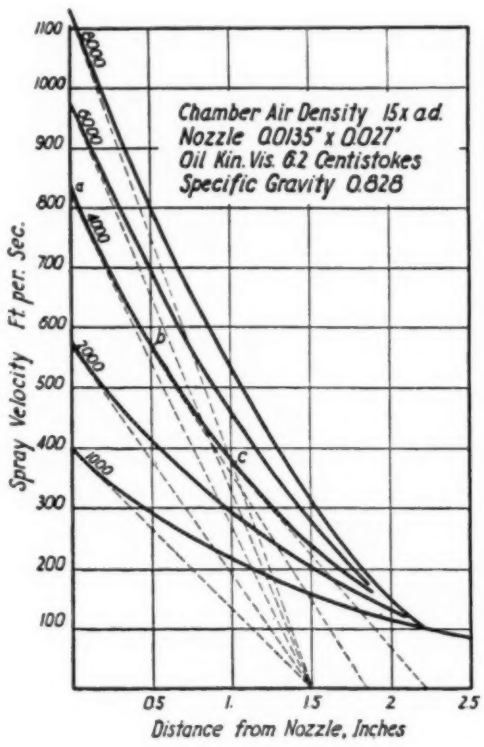


FIG. 8. Spray velocities. Effect of injection pressure. Dotted lines show that the curves have equal subtangents.

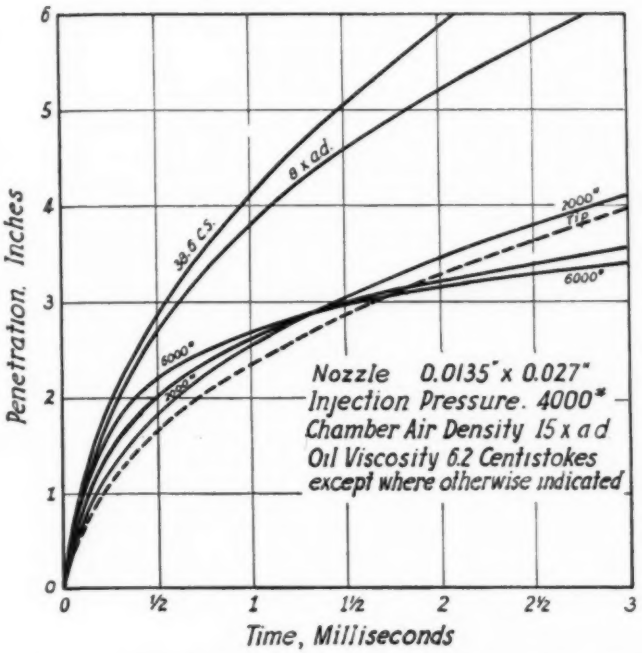


FIG. 9. Penetration of the "average globule." These curves were obtained by graphical conversion from the mean spray velocity curves. Note the negligible effect of the injection pressure. The dotted line shows the penetration of the spray tip for comparison.

A great number of measurements were taken, with three different orifice diameters and five different oils to determine the effect of orifice diameter, oil viscosity, and specific gravity in addition to the above-mentioned variables. The reproduction of the results would take too much space but fortunately the data permitted us to establish a theory which takes care of all these variables and permits the calculation of the spray velocity at any distance for any set of conditions.

The results of the theory verified experimentally can be summed up as follows:

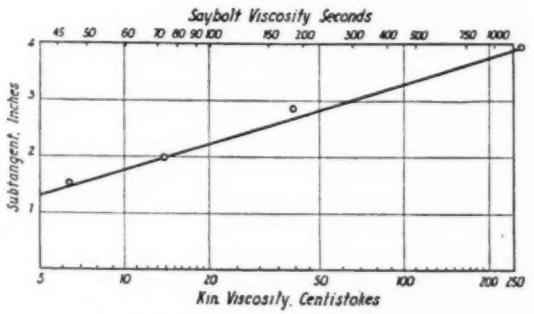


FIG. 10. Subtangents of spray velocities of 15 times atmospheric air density.

1. The issue velocity of the oil spray depends essentially on the injection pressure and can be calculated with the well-known hydraulic formula $v = c(2gh)^{\frac{1}{2}}$, using a velocity coefficient of 0.95 for slightly rounded cylindrical orifices. The issue velocity is independent of the orifice size and the oil viscosity and practically independent of the chamber air density.

2. The air resistance to the spray generally follows the square law. The only exceptions to this are in the region of low air density, high oil viscosity and large nozzle orifices not representative of ordinary Diesel engine practice.

3. The air resistance under circumstances normally encountered by a Diesel spray varies as the first power of the air density and it is independent of the orifice size.

4. The air resistance decreases with increasing oil viscosity (see Fig. 10), but is not sensitive to normal changes in specific gravity.

5. The curve representing the mean spray velocity plotted against penetration distance has equal subtangents at any point and the

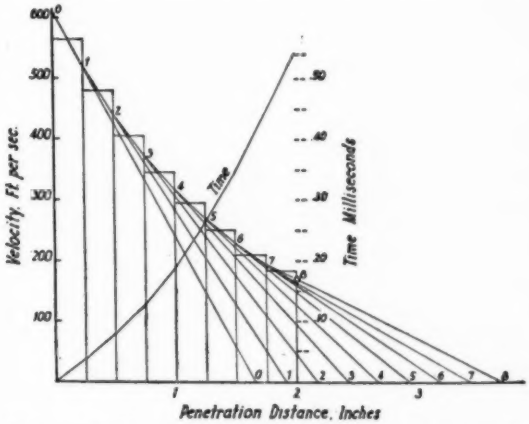


FIG. 11. Constructing spray velocity curve, example.

subtangents are identical for any injection pressure (see Fig. 8) but they will vary as the reciprocal of the chamber air density. This is a consequence of (2) and (3), the mathematical derivation of which is given.[4]

As a result of these findings, rules can be presented for the calculation of spray penetration

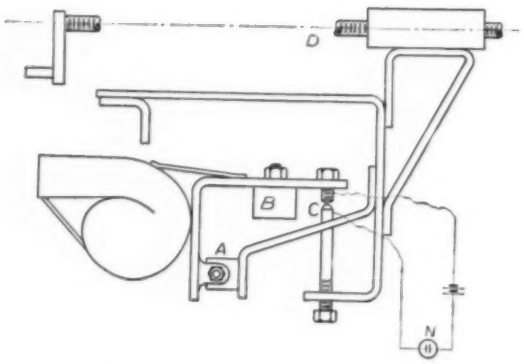


FIG. 12. Tipping cup. When the oil deposited in the cup exceeds a predetermined weight, the cup tips and by breaking electric contact at C turns off the neon light N.

and velocity. The steps of the calculations will be shown on an example.

EXAMPLE

An engine has a spray nozzle with one 0.020 in. diameter orifice. The effective injection pressure is 3000 lb. per sq. in. The compression ratio of the engine is 14 : 1. An oil of 50 Saybolt sec. viscosity is used. What will be the velocity of the spray 2 in. from the nozzle and how long does it take the average globule to travel that distance?

The compression pressure at top dead center will be

$$p_c = 14.7 \times 14^{1.3} = 455 \text{ lb. per sq. in.}$$

Assuming a specific gravity of 0.90, the issue velocity of the spray will be

$$v_0 = 0.95(2 \times 32((3000-455)144)/(0.9 \times 62.25))^{\frac{1}{2}} = 614 \text{ ft./sec.}$$

As the next step we determine the characteristic

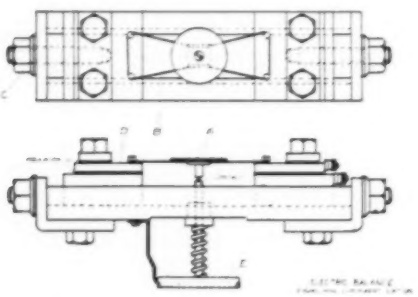


FIG. 13. Electric balance for measuring dynamic pressure of spray.

subtangent of the spray velocity curve. From Fig. 10, the subtangent corresponding to 50 sec. Saybolt is 1.55 in. This refers to 15 × atmospheric density. We have (at top dead center) only 14 × atmos. density and the subtangent will be correspondingly longer

$$u = (15/14)1.55 = 1.66 \text{ in.}$$

Now we proceed with the construction of the spray velocity curve, Fig. 11, which consists of

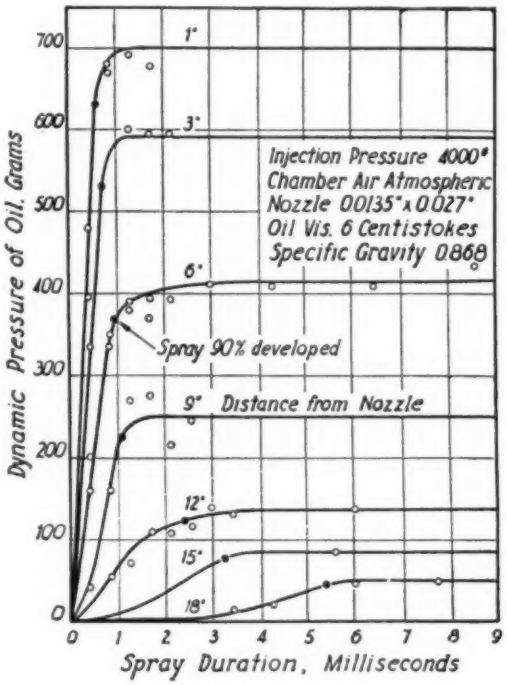


FIG. 14. Building up of a 4000 lb. spray.

drawing an envelope step by step, maintaining a subtangent of 1.66 in. As a result of 2 in. distance a spray velocity of 170 ft. per sec. is obtained, 28 percent of the original issue velocity.

For calculating the elapsed time we can use the point to point method. For the first $\frac{1}{4}$ in. distance the globule is assumed to have an average velocity of $\frac{1}{2}(613+520) = 565$ ft. per sec. and therefore to cover that distance takes $0.25/12/565 = 0.000037$ sec. or 37 microsec. The further calculation is tabulated in Table I.

The result of the calculation is that it takes the average droplet a little more than one half-thousandth of a second to travel 2 in. distance from the nozzle and by that time it has lost almost $\frac{3}{4}$ of its velocity.

TABLE I.

PENETRATION INCHES	VELOCITY LINE	AVERAGE VELOCITY	TIME = DISTANCE / VELOCITY MICROSECONDS
$\frac{1}{4}$	0–1	565	37
$\frac{1}{2}$	1–2	480	43
$\frac{3}{4}$	2–3	405	52
1	3–4	345	60
$1\frac{1}{4}$	4–5	295	71
$1\frac{1}{2}$	5–6	250	83
$1\frac{3}{4}$	6–7	210	99
2	7–8	183	114
	Total		559

Experiments with the tipping cup, Fig. 12, substantially confirmed the results of the ballistic pendulum.

BUILDING-UP PERIOD OF SPRAY

Sprays of short duration have been investigated to learn the characteristics of such sprays and get an insight into the building-up process. A spray has to complete its air boring process before it attains equilibrium, therefore its characteristics are different at the beginning of the injection than later.

The experiments were made with a slotted disk and with a very quick-acting electromagnetic spray valve. The dynamic force ("hardness") was measured by an electric balance, Fig. 13. The tests showed that the building-up period is extremely rapid. As shown on Fig. 14, it increases with the distance but even at 6 in. distance the spray is 90 percent developed in about one millisecond. Injection pressure and chamber pressure have only slight effect on the length of the building-up period.

High speed Diesel engines have injection periods of not less than 30 degrees pump angle at 1500 r.p.m. pump speed. The duration of the injection is, therefore, 1/300 sec. Even this very short duration is much longer than the aerodynamic building-up period. Therefore, it may be stated that the spray in ordinary Diesel engines is not influenced by the injection duration, and the penetration of a short intermittent spray is the same as of a stationary spray. Exceptions to this are sprays of extremely short duration, not typical with the conventional injection systems.

References

1. D. W. Lee, "A Comparison of Fuel Sprays from Several Types of Injection Nozzles," N.A.C.A. Tech. Report No. **520** (1935). (This contains a very complete bibliography of the N.A.C.A. publications on the subject.)
2. F. Sass, *Kompressorlose Dieselmaschinen* (Julius Springer, Berlin, 1929.)
3. O. Holfelder, Der Einspritzvorgang bei Dieselmotoren. Zeitschrift, V.D.I. **76**, 1241 (1932).
4. P. H. Schweitzer, "Penetration of Oil Sprays," The Pennsylvania State College Engineering Experiment Station Bulletin No. **46** (1937).
5. A. G. Gellales, "Effect of Length Diameter Ratio on Fuel Sprays, etc." N.A.C.A. Tech. Report No. **402** (1931).
6. E. G. Beardsley, "The N.A.C.A. Photographic Apparatus for Studying Fuel Sprays, etc." N.A.C.A. Tech. Report No. **274** (1927).

Resumés of Recent Research

Recent advances in experimental and theoretical physics are described in these columns in nontechnical language. It is intended that sufficient background be given to introduce the reader to the subject.

Improvements in Phonograph Reproducers

Interest in the use of phonograph recording on disk materials suitable for immediate playback has been heightened by recent improvements in reproducer design[1] and a detailed study of the motion of a needle tip in a record groove.[2] The latter paper analyzes the distortion generated by the use of a reproducer stylus tip of finite size, showing that, if the stylus tip can be positively guided by both sidewalls of the groove at all times, a lateral-cut record is more free from distortion than a similarly engraved vertical-cut record. This is because the former offers the advantages of a mechanical push-pull system with consequent cancellation of all even-order distortion products.

Positive tracking is not ordinarily attained because the included angle of the record groove varies when the recording stylus moves, as it commonly does, with a transverse velocity which is not negligible with respect to the tangential groove velocity. Conventional reproducers cause both needle tip and record to wear excessively in the pinched sections of the groove, with subsequent loss of positive tracking and an increase of distortion and noise. On the other hand, if the reproducer design provides for vertical mobility of the needle tip at signal frequencies, the tip can rise and fall in the groove as the included angle varies; in fact such vertical motion represents the even harmonic distortion that is canceled out of the lateral motion. Measurements of the distortion observed under these conditions are in good agreement with the predictions of the analysis.

In the communications profession the opinion has been commonly held that vertical-cut transcription records are the finest now made, and that high fidelity reproduction for the home must await the commercial availability of such records and reproducing equipment. It now appears that the unquestioned merit of these records is to be ascribed to more effective instrumentation and improvements in the processing art rather than to any intrinsic advantage of the hill-and-dale type of recording. The papers here reviewed give reason to hope that the adoption of these techniques in the manufacture of lateral-cut records will make an even higher standard of fidelity easily available to the users of phonograph equipment.

[1] F. V. Hunt and J. A. Pierce, Electronics **11**, 9 (1938).
[2] J. A. Pierce and F. V. Hunt, J. Acous. Soc. Am. **10**, 14 (1938); J. Soc. Mot. Pict. Eng. **31**, 157 (1938).

A New Precision Method for the Determination of e/m for Electrons

Practically every method that has been used for the measurement of e/m for electrons by deflection in a field of force requires a knowledge of the velocity of the electrons. The determination of this velocity is rendered uncertain by the presence of polarization layers which form on the slit that is used to collimate the electron beam. These polarization layers give rise to a retarding field in the vicinity of the slit and hence the applied accelerating potential does not provide a true measure of the velocity of the electrons.

Recently, Dr. A. E. Shaw[1] at the University of Chicago has developed a new method in which the velocity does not appear explicitly in the final equation for e/m. In this method the electrons are focused under the simultaneous action of electric and magnetic forces, as indicated in the figure. The electric force arises between the plates of a cylindrical condenser and the magnetic force is produced by a symmetrical pair of coils whose axis is normal to the

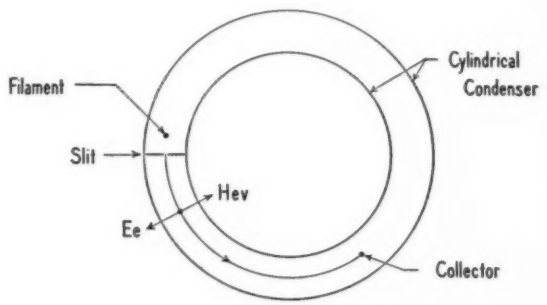
[1] A. E. Shaw, Phys. Rev. **54**, 193 (1938).

plane of the orbit. Under these conditions the electric and magnetic forces lie in the plane of the orbit, as shown.

The equation for e/m is,

$$e/m = 4E/(H^2\rho),$$

where E is the electric field intensity, H is the magnetic field intensity and ρ is the radius of curvature of the circular orbit. The point of focus is 127° 17′ from the slit. Although the equation for e/m does not require that the electron velocity be known in order to determine e/m, nevertheless, only electrons of a certain voltage equivalent will reach the collector for given electric and magnetic field intensities. This voltage equivalent is determined by means of focusing criteria which in effect utilize the electrons after they have emerged from the slit. Thus, in the method of crossed electric and magnetic fields, the focusing is carried out with electrons whose effective velocity after emergence from the slit is known precisely from the electric and magnetic forces operating. Therefore, any



Section through cylindrical condenser showing forces which act on the electron beam to focus it on to the collector.

retardation experienced in the region of the slit does not constitute an uncertainty in this method of measuring e/m. Furthermore, the difference between the applied accelerating potential and the voltage equivalent is a measure of the magnitude of the polarization layer.

The magnitude of the polarization layer varies with the applied accelerating potential. When the applied accelerating potential was 120 volts, the polarization layer was approximately 10 volts and when the applied accelerating potential was 400 volts the polarization layer was approximately 25 volts.

The value of e/m obtained with the present apparatus is $e/m_0 = (1.7571 \pm 0.0013) \times 10^7$ e.m.u. Because of the physical limitations of the present cylindrical condenser, no attempt was made to push this determination to the extreme limits of accuracy attainable with this new method. However, it is hoped that with a new cylindrical condenser it will be possible to determine e/m to within a probable error of 1 : 3000.

Recent Advances in Slow Neutron Technique

The neutrons which Chadwick first observed in 1932 had speeds close to that of light. But Fermi soon showed that they could be slowed to thermal velocities by a succession of "billiard ball" collisions with the hydrogen atoms in paraffin. "Thermal neutrons" are the most effective agents for the disintegration of nuclei, so a study of their properties is of great importance in nuclear physics. Experimental investigations of slow neutrons have been hampered in the past by (1) the fast neutron background always present, (2) the broad energy band (Maxwell distribution) with which one must work, (3) the impossibility of achieving good collimation, and (4) the inability of liquid hydrogen to "cool" neutrons much below the temperature of liquid air. (Many thermal neutron effects are greatly enhanced when the neutrons have slower velocities.)

An experimental arrangement which eliminates these four difficulties has recently been described by Luis W. Alvarez[1] of the University of California's Radiation Laboratory; the apparatus is essentially a velocity selector. Fast neutrons are generated in short pulses 60 times a second. A detector placed several meters from the paraffin in which the neutrons are showed down is arranged to be insensitive to neutrons except for a short time each cycle, when no fast neutrons are being formed; thus no fast neutrons are detected. But thermal neutrons take an appreciable fraction of a cycle to traverse the source-detector distance, so they are recorded. When suitable screens of cadmium are placed around the apparatus, it may be shown that

[1] Phys. Rev. **54**, 486 (1938).

the thermal neutron beam is highly collimated. By changing the source-detector distance, or by altering the modulation-phase-shift time, it is possible to work with neutrons of any particular temperature from 300° to 10° absolute. The method, therefore, opens for exploration several new fields of research, including the neutron spectroscopy of the "far infra-red."

Polymorphic Transformations under Pressure Structural transformations take place in many substances when they are subjected to very high pressures. The change in volume which accompanies such transformations is the usual criterion for determining their existence. Many valuable thermodynamic data may be obtained simply from a knowledge of the volume changes alone. However, the very interesting problem as to why and when a transformation will occur in a given material cannot be solved without more information than this type of experiment offers. In particular, a knowledge of the atomic arrangement is needed; i.e., the crystal structures must be known. An x-ray camera which will produce powder photographs of substances under pressure has been built recently by R. B. Jacobs at Harvard University.[1] This apparatus has been successfully used to determine crystal structures of samples under pressures as high as 5000 atmospheres. Several simple salts have been studied under pressure and their crystal structures determined. The information so obtained has been used by Jacobs to calculate the theoretical pressures at which the transformations should occur. In the chemical series of the rubidium and potassium halides the calculated transformations are in agreement with the experimental as far as order of occurrence with increasing pressure is concerned. Likewise, a good numerical agreement is found between the theoretical and experimental volume changes at the transition points. The sodium salts (in contrast to the potassium and the rubidium) fail to show transitions up to pressures of 50,000 atmospheres, the present upper limit of Bridgman's high pressure measurements. In this case, the same type of calculations predict that no transformation of the rubidium and potassium types should occur at any pressure. The complete verification of these calculations, of course, awaits the extension of the present pressure range.

[1] Phys. Rev. **54**, 325 (1938); Phys. Rev. **54**, 468 (1938).

Finite Solid Acoustic Filters A solid rod can be so treated that when one end of it is vibrated longitudinally only those vibrations corresponding to certain frequencies will be able to travel along it.[1] A steel rod, like that in Fig. 1, loaded

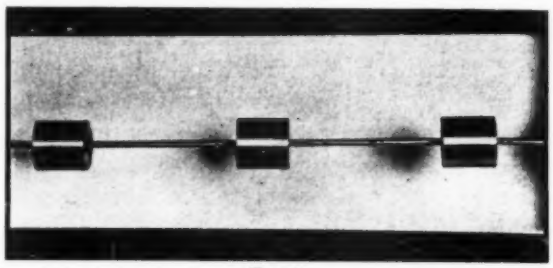


FIG. 1.

at equal intervals with heavy steel collars, is found to act as a low pass filter for compressional elastic waves in much the same way as certain repeated combinations of resistance, inductance and capacitance act as electric wave filters. The theory for the ideal case of an *infinite* structure of the kind shown has already been developed previously but now for the first time study has been made both theoretically and experimentally of a *finite* solid filter with a finite termination such as may actually be built. In the experimental test the rod, consisting of six sections, was vibrated by having one end of it rigidly attached to a magnet inserted into a coil carrying the amplified output of a beat frequency oscillator. The vibrations were detected by piezoelectric phonograph pick-ups placed before and after the filter structure. The theoretical transmission region from 0 to 2000 cycles and its six high peaks were found to be in good general agreement with experiment.

Solid filters of the kind described may ultimately prove of value in reducing the effects of machinery vibration. In fact much machinery vibration damping is already based on the filtration principle.

[1] Cf. R. B. Lindsay and A. B. Focke, "Finite Solid Acoustic Filters," J. Acous. Soc. Am. **10**, 41 (1938).

Crystal Structure from X-Ray Data When a beam of x-rays is sent through crystalline matter, it is diffracted into a number of beams. These manifest themselves as localizations of energy upon any receiving apparatus, such as a photographic plate or an ionization chamber, placed in the path of the diffracted radiation. Whether these localizations are in the nature of spots or lines depends on the experimental procedure and the condition of the test material, whether single or multicrystalline. In any case, with each such localization of energy there may be associated three integers, the so-called "Laue indices," (*hkl*). From the experimentally observed intensities of any diffracted beam associated with indices (*hkl*), one may compute a proportionate quantity, the square of the "crystal structure factor" for (*hkl*).

The crystal structure factors are related by theory to the distribution and scattering powers of the atoms in the unit cell of the crystal. To determine the location of these scattering centers is one of the main problems. In the past, crystallographers have resorted primarily to methods of trial and error in dealing with it. In a paper published recently* by M. Avrami the similarity in the behavior of scattering factor curves for different atoms is used to derive a system of algebraic equations whose coefficients are calculated from these curves and the experimental data for any given crystal. Depending upon the nature of the data, the roots of these equations give directly either the coordinates of the unknown atomic positions, or those of the interatomic distances from which the unknown parameters themselves may readily be determined. The method is applied to the KH_2PO_4 crystal, and the results are found to compare very well with the values found by J. West on the basis of a trial-error and Fourier synthesis investigation.

* "Direct Determination of Crystal Structure from X-Ray Data," Phys. Rev. **54**, 300 (1938).

Temperature Scale for Rhodium In a current article in the *Journal of Chemical Physics*, Wahlin and Whitney present results on the emissivity and thermionic properties of rhodium. These observers have shown that a high emissivity surface, which appears when the temperature of the metal is lowered from about 1300°C to a lower value (this being done in a vacuum), is caused by the sudden appearance of an oxide layer. The reason for believing this is that the temperature at which the change takes place is a function of the partial oxygen pressure.

This effect has in the past been ascribed to some structure change in the metal. Wensel and Tuckerman in an article in the August number of the *Review of Scientific Instruments* point out that the structure change idea is not tenable and that the effect is probably caused by an oxide film. This is in line with the findings of Wahlin and Whitney.

Continued heat treatment in a vacuum of $2\text{–}3\times10^{-8}$ mm of Hg will cause the complete disappearance of the oxide layer at all temperatures. The emissivity for such a clean surface is found to be 0.242 for a wave-length of 6698A. This gives a temperature scale as follows:

True Temp. °K	Apparent Temp. °K
1200	1111
1300	1197
1400	1282
1500	1365
1600	1447
1700	1528
1800	1609
1900	1689
2000	1768
2100	1847

The thermionic study carried out with a U-shaped filament in a single guard ring tube gave a work function of 4.80 volts for the clean surface with an A in Richardson's equation of 33 amp. cm^{-2} $degree^{-2}$.

Evidence for the Existence of a New Elementary Particle

BY ENOS E. WITMER AND MARTIN A. POMERANTZ

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FOR several decades prior to 1932, physicists generally assumed that the proton and the electron were the only elementary units of matter. Then the neutron and the positron were discovered in rapid succession as a result of nuclear and cosmic-ray investigations. The neutrino was postulated for theoretical reasons. Recently cosmic-ray research has apparently resulted in the discovery of another elementary particle, the *heavy electron*, which has the same charge, either positive or negative, as the ordinary electron, but a larger mass. Consequently, it would seem to be more logical to speak of two new elementary particles (at least if the positron is regarded as distinct from the negative electron), although even this may be an understatement of the number, in view of the fact that it is not certain whether the mass is unique. However, in this paper in conformity with present practice the term "(heavy) electron" when unmodified will refer to both positive and negative (heavy) electrons. The term "heavy electron," although appropriate, is often inconvenient. The word "*barytron*" (Greek βαρυς, heavy) has been proposed as a permanent name for the new particle. Another name which has been suggested is the "*yukon*." In the sequel, a survey of the principal evidence for the existence and nature of the barytron will be presented.

The main methods of cosmic-ray investigation utilize ionization chambers, Geiger counters, and Wilson cloud chambers. The latter method offers the advantage of yielding precise knowledge about individual particles, whereas the first two afford statistical information concerning cosmic radiation. The evidence under consideration is, therefore, divided into two categories, which may be termed *direct* and *statistical*.

Since the success of the Lemaitre-Vallarta theory[1] in explaining the latitude effect, it has been generally agreed that cosmic rays consist predominantly of charged particles of enormous energy, even up to the order of magnitude of 10^{12} ev. It has also been demonstrated that there are two components[2] in the cosmic radiation, one of which is easily absorbed and is therefore called *soft*, whereas the other, being very penetrating, is designated *hard*. It should be emphasized that these terms do not refer to the energy of the particles, but merely their penetrability. The soft component is now believed to consist predominantly of electrons, but the nature of the particles in the hard component has not yet been ascertained beyond doubt. It is investigations of the latter component that furnish the evidence for the existence of the barytron.

THEORY OF ENERGY LOSSES AND SECONDARY PROCESSES

In order to study this evidence it is necessary to consider the theory of absorption of fast particles in traversing matter.

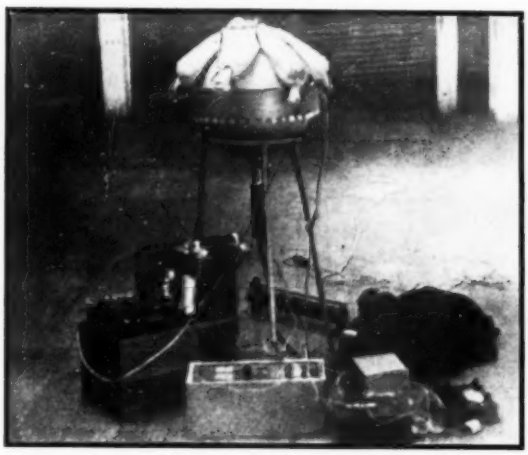


FIG. 1. Ionization chamber and associated apparatus used at the Bartol Research Foundation of the Franklin Institute. The large sphere is the ionization chamber which records the size of atomic bursts that originate in the bags of lead shot on top of the ionization chamber.

According to existing theory a charged particle in passing through matter loses energy principally by the following processes: (1) Ionization by collision. (2) Emission of radiation (Bremsstrahlung), i.e., the production of γ-rays by close encounter with atomic nuclei, this being analogous to the production of general x-radiation in an x-ray tube.

Collisions with nuclei also contribute to a comparatively small extent and hence have been neglected in the calculations.

Theoretical formulas have been developed for the loss of energy by fast particles of electronic charge in each of these processes. Graphs of the energy loss as a function of the energy possessed by the particle are shown in Fig. 3.

Bethe[3] has calculated the loss of energy per unit of path due to ionization. Since the cosmic-ray particles are endowed with such great energy, these calculations must be made on the basis of the theory of relativity. The formula is

$$-\left(\frac{dE}{dx}\right)_{\text{ion}}=\frac{4\pi e^4NZ}{mV^2}\left\{\log\frac{2mV^2}{\bar{I}(1-\beta^2)}-\beta^2\right\}. \quad (1)$$

Here N is the number of atoms per cm^3 in the absorbing medium, Z is the atomic number of the material of the medium, E is the energy of the particle, V its velocity, e is the electronic charge in e.s.u., m is the rest mass of the electron, $\beta=V/c$, and $\bar{I}$ is the mean ionization energy in ergs, which may be taken equal to $RhcZ$, where R is the Rydberg number in cm^{-1}. For very high energies ($E\gg mc^2$) Bethe gives a simpler formula:

$$-\left(\frac{dE}{dx}\right)_{\text{ion}}=\frac{2\pi e^4NZ}{mc^2}\log\frac{E^2}{2mc^2\bar{I}^2}. \quad (2)$$

The theory of the radiative losses for a particle of mass M was developed by Bethe and Heitler,[4] who obtained the following formula:

$$-\left(\frac{dE}{dx}\right)_{\text{rad}}=N\frac{Z^2}{137}\left(\frac{e^2}{Mc^2}\right)^2E\Phi, \quad (3)$$

where

$$\Phi=4\log[2E/Mc^2]-4/3 \quad (4)$$

for

$$Mc^2\ll E\ll 137Mc^2Z^{-\frac{1}{3}}$$

and

$$\Phi=4\log[183(M/m)Z^{-\frac{1}{3}}]+2/9 \quad (5)$$

for

$$E\gg 137Mc^2Z^{-\frac{1}{3}}.$$

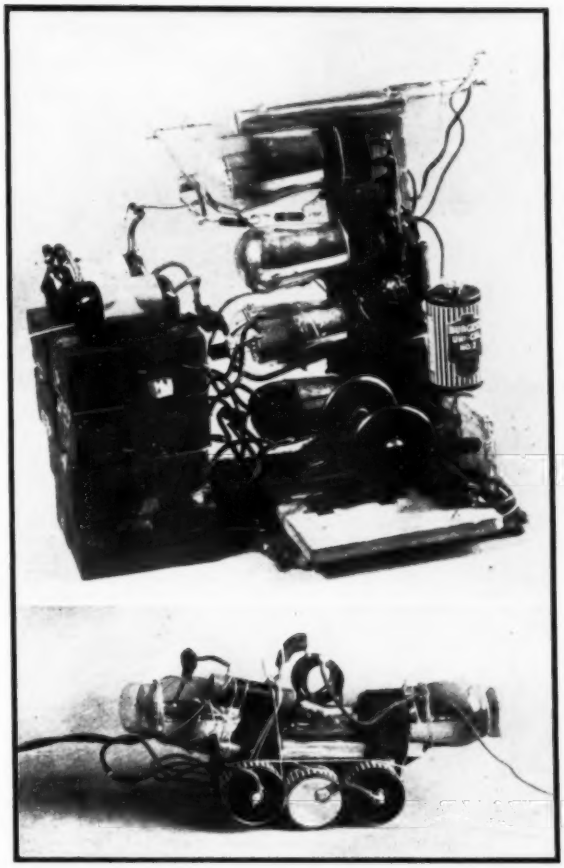


FIG. 2. Balloon apparatus used at the Bartol Research Foundation of the Franklin Institute, showing barograph, batteries, cosmic-ray counting tube, radio tubes, and transmitter below.

Formula (4) differs from formula (5), because in the former case of low energies the shielding effect of the extranuclear electrons on the field of the nucleus is negligible, whereas in the latter case this so-called *screening* must be considered.

From Eqs. (2) and (3) an approximate ratio[5] of the radiative losses to the ionization losses may be obtained:

$$\frac{-(dE/dx)_{\text{rad}}}{-(dE/dx)_{\text{ion}}}=\frac{ZE}{1300mc^2}\left(\frac{m}{M}\right)^2. \quad (6)$$

This shows that the radiative losses become increasingly predominant as the energy of the penetrating particle increases. It is worth noting that the radiative losses are roughly proportional to Z^2 and the ionization losses to Z. Eq. (6) also indicates that the ratio of the radiative to the

ionization losses is inversely proportional to the square of the mass of the particle.

Closely associated with the radiation produced by a penetrating particle is *pair production*, the creation of a pair of positive and negative electrons by a γ-ray resulting from process (2). Fig. 4 shows the production of a pair of positive and negative electrons in an axial magnetic field. Notice the different curvatures of the paths.

On the basis of the elementary processes outlined above, Bhabha and Heitler,[6] and Carlson and Oppenheimer[7] have constructed the *cascade* or *multiplicative* theory of showers. A shower is a rapid increase in the number of fast particles in a limited region. This increase is accounted for by the alternate occurrence of radiation and pair production, hence the term *cascade*. Thus a fast particle produces by process (2) a γ-ray which moves in almost the same direction as the emitting particle. This γ-ray then produces an electron pair, which retains roughly the original direction. Each of the electrons may in turn produce γ-rays, and so on until the resulting electrons or photons have insufficient energy to continue the process. A shower is shown in Fig. 5.

The Statistical Evidence

On the basis of the theory presented above, the experimental results for the soft component of the cosmic radiation can be accounted for on the assumption that it consists predominantly of positive and negative electrons. Thus the calculated intensity of this component as a function of altitude is in agreement with the observations, as is the increase of shower intensity with altitude.[8] This affords also an experimental check of the formulas stated above, which had not been previously obtained in this high energy range.

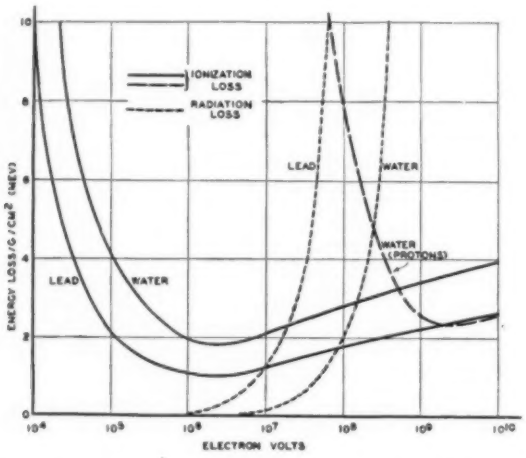


FIG. 3. Energy loss of electrons by ionization and radiation. The ionization loss by protons in water is shown for comparison.

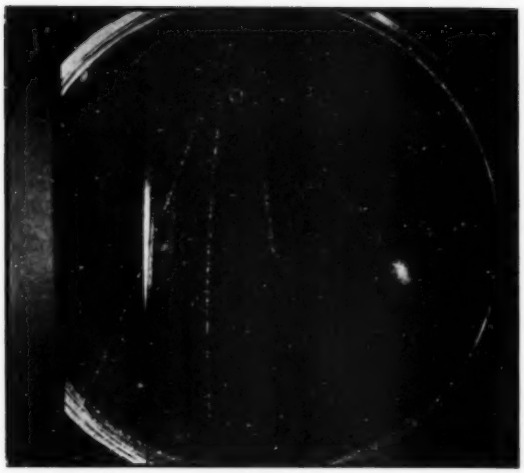


FIG. 4. Wilson cloud-chamber photograph made with an axial magnetic field, showing the production of a pair of positive and negative electrons. (From J. C. Street and E. C. Stevenson.)

But the hard component cannot be explained on the assumption that it consists of ordinary electrons which conform to the existing theory. Therefore, two alternative hypotheses[9] have been proposed:

(a) The existing theory breaks down for electrons with an energy greater than some critical energy, E_c.

(b) The hard component does not consist of ordinary electrons.

Hypothesis (a)

It has been pointed out by various investigators[5, 9] that this hypothesis leads to conclusions in contradiction with the experimental data and must therefore be rejected. Nordheim[10] has calculated the intensity of the cosmic radiation as a function of altitude at different latitudes on the assumption that it consists of electrons which conform to existing theory. He finds good agreement with observation at high altitudes, but at low altitudes, where the hard component comprises the bulk of the radiation, a discrepancy exists between calculated and observed intensity. He concludes that the fit between the experi-

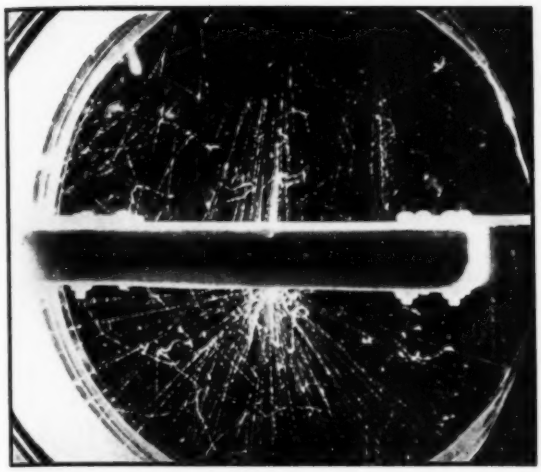


FIG. 5. A shower originating in a lead plate in a Wilson cloud chamber. (From R. B. Brode.)

mental and theoretical curves cannot be improved by assumption (a) and that the curves suggest strongly the validity of the radiation theory up to at least 18×10^9 ev.

The present theory gives a good representation of the shower phenomena both in the atmosphere[8] and in absorbing media such as lead.[9] In the latter case the theory[5, 6] predicts the shape of the *transition curve*,[2] which is a plot of the number of showers containing a given number of particles as a function of the thickness of the material in which they are produced.

Hypothesis (*b*)

A cogent argument in support of hypothesis (*b*) is based upon the observation that the hard component exhibits a penetrability which is many times greater than that corresponding to an ordinary electron with any reasonable energy, for such electrons[8] would be absorbed in about 10 to 15 meters of water, or 10 to 15 kilometers of normal air. The hard component, however, has been observed at depths of 1400 meters water-equivalent[11] from the top of the atmosphere. Furthermore the hard particles produce very few showers, which would not be the case if they were ordinary electrons.

Various experiments indicate that the hard component obeys a mass-absorption law,[12] i.e., the absorption depends only on the intervening mass, and not on the atomic number of the medium. By inspection of formulas (1), (2) and (3), it is obvious that this fact does not accord with the supposition that the hard particles are electrons.

Nordheim[10] has accounted for the observed variation of cosmic-ray intensity with altitude at different latitudes by assuming that, in addition to the soft component, there is a hard component which does not consist of ordinary electrons. It should be stated, however, that he uses an empirical absorption law for the hard component.

Therefore, the evidence points to the conclusion that *the hard component does not consist of ordinary electrons.*

In view of their high penetrability, and the direct evidence which will be presented in the sequel, the proposal has been made that the hard particles have electronic charge but a rest mass greater than that of an ordinary electron. (This should not be interpreted as precluding the possibility of the presence of other particles in the hard component.)

As formula (3) indicates, the radiative losses are roughly inversely proportional to the square

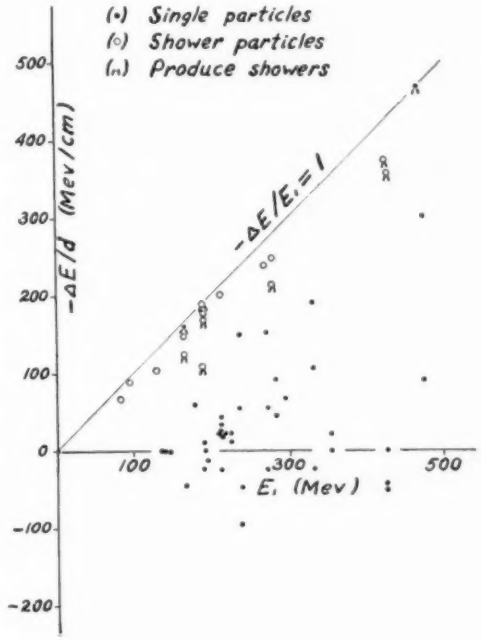


FIG. 6. Energy loss of cosmic-ray particles in 1 cm of platinum. Note that the shower particles lose energy more rapidly than the single particles. (From Neddermeyer and Anderson.[14])

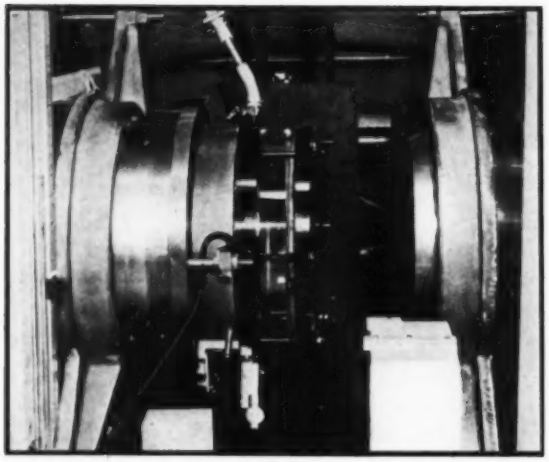


FIG. 7. Wilson cloud-chamber apparatus. (From Street and Stevenson.)

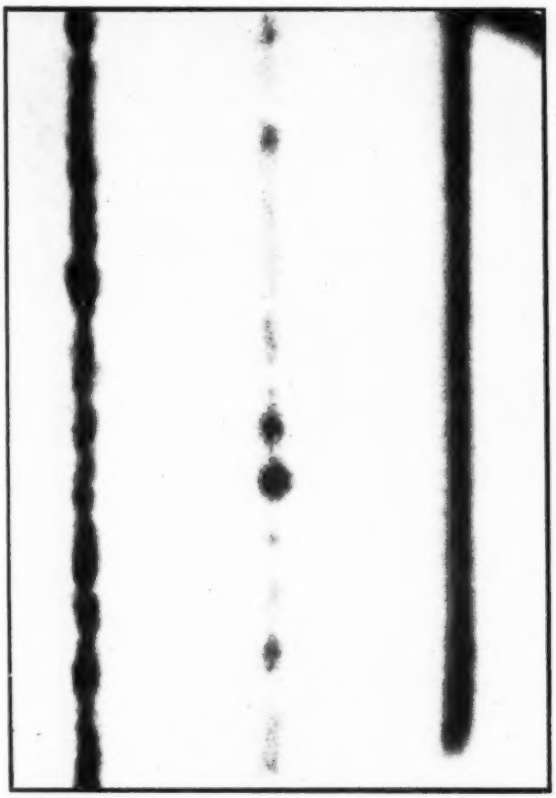
of the mass, M. Consequently, for a given energy the penetrability of a heavy particle will exceed that of an ordinary electron. It also follows that a decrease in the radiation will result in correspondingly fewer secondaries and showers according to the multiplicative theory. This is also in agreement with experiment.[13] In fact, the evidence[14] is so striking in this respect that the hard component has been termed *nonshower-producing* in contrast with the soft component which has been designated *shower-producing*. This terminology does not imply that the hard particles are incapable of producings howers, but rather that the probability is comparatively small.

There is, as yet, no universal agreement on the basis of the statistical evidence, concerning the magnitude of the mass of these heavy particles. However Bhabha[5] maintains that a large number of experimental facts can be accounted for by ascribing to them a rest mass of about 100 m. Nevertheless, difficulties remain and he offers the further possibility that quantum jumps in the rest mass may occur, thus rendering the mass variable. Neddermeyer[15] advanced a somewhat similar proposal that mass is quantized, and that various rest masses are possible for a particle of electronic charge.

DIRECT EVIDENCE

The more direct and convincing evidence for the existence of a new elementary particle is based upon the results of Wilson cloud-chamber experiments. In this type of investigation, opportunity is afforded for directly studying the nature of individual particles. Due to the dependence of the ionizing power of a particle of given energy upon its nature, it is possible to distinguish between those of various charges and masses.

In a Wilson cloud chamber, in which a volume of gas containing a saturated vapor is adiabatically expanded to give a short interval of supersaturation, the ions produced along the path of a charged particle traversing the chamber act as condensation nuclei for the vapor. It is obvious that formulas (1) and (2) give the specific ionization of the gas in the chamber if one divides by the average energy loss per ion pair. However, the ionization density of a fast particle depends only upon its charge and velocity, and not upon its rest mass, according to these formulas. Hence,



(a) (b) (c)

FIG. 8. (a) Enlarged track of a heavy particle that apparently tripped the counters. (b) Electron track taken under same conditions. (c) Track of a fresh alpha-particle. (Magnification 3×.) (From Brode, MacPherson and Starr.[17])

two particles of different rest masses will have the same ionizing power if their velocities and charges are the same. In principle this permits a determination of the velocity if the charge is known.

If the momentum is known, therefore, the rest mass may be calculated. The value of the momentum is furnished by the curvature of the path of the charged particle subjected to a known magnetic field, according to the formula:

$$H\rho = MVc/(e(1-V^2/c^2)^{\frac{1}{2}}) = pc/e, \qquad (7)$$

where H is the magnetic field strength, ρ is the radius of curvature of the trajectory, and p is the relativistic momentum.

It should be pointed out that this method of determining the mass is effective only when the velocity of the particle is not too great, because, as may be seen from the curves for the proton and the electron in Fig. 3, at high energies the rate of ionization does not depend to any great extent on the rest mass of the particle. (The dependence on the rest mass shown in Fig. 3 does not contradict the statement above that the rate of ionization does not depend on the rest mass, because the abscissa in Fig. 3 is the *energy*, not the *velocity* of the particle.) This necessitates studying the path near the end of the range of the penetrating particle. This is accomplished by the use of absorbing material, and suitable coincidence counter circuits which actuate the Wilson cloud chamber only when the traversing particle is near the end of its range.

Alternative methods[16] of estimating the rest mass utilize measurements of the range, the rates of change along the track of specific ionization and of curvature, and $H\rho$, at least two quantities being necessary for a determination.

Inasmuch as the direction of curvature is dependent upon the sign of the charge, further information is thus revealed by a photograph of a cloud-chamber track. Various clues may enable one to deduce the probable direction of motion of the particle. For example, after traversing a metal plate, the particle must be assumed to have traveled from the side of greater $H\rho$ to that of lesser (unless energy is gained in the plate). The direction of a secondary produced by a collision with an electron indicates the direction of the colliding particle. A diverging group of tracks suggests, with high probability, although not with certainty, that each particle moved away from the region. Since the primary cosmic radiation originates outside the earth's atmosphere, a particle producing a vertical track was probably traveling downwards.

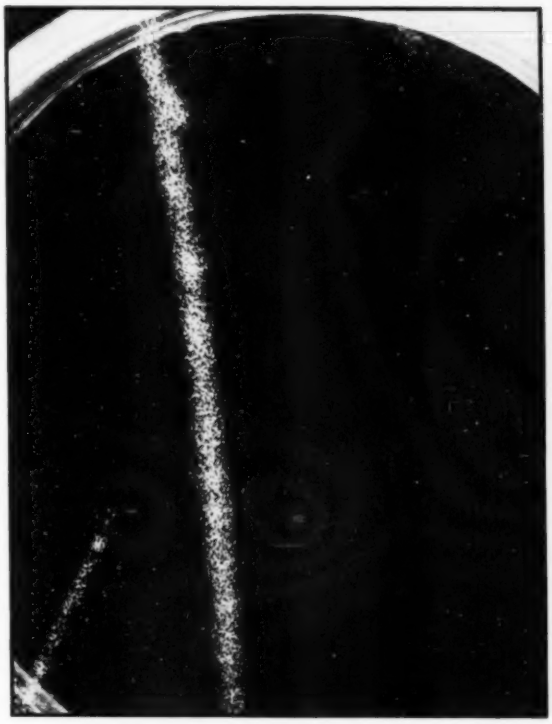


FIG. 9. Wilson cloud-chamber photograph of a heavy track. The density of ionization in this track is about 5.5 times that of an ordinary cosmic-ray track. The value of $H\rho = 1.5 \times 10^5$ gives a mass of 250 times the mass of an electron. (From D. R. Corson and R. B. Brode.[16])

The specific ionization is determined by counting the number of droplets per unit length along the path after allowing the ions to diffuse somewhat in order to render the droplets visible individually. This is accomplished by using the counter-control method of actuating the cloud chamber (in which case a photograph is obtained only when a coincidence occurs between suitably situated Geiger counters) in conjunction with a delayed expansion mechanism. It is necessary to apply various corrections to the data.

It is well known that protons ionize much more intensely near the end of their range than electrons (Fig. 3). Up to the end of 1936 several investigators[9, 17] had reported heavy tracks in

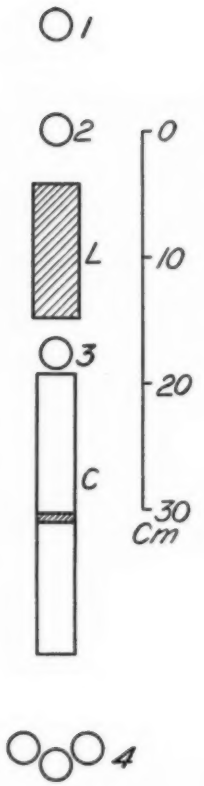


FIG. 10(a). Schematic diagram of the apparatus used by Street and Stevenson[18] in obtaining the track shown in Fig. 10(b). The circles 1, 2, 3, and 4 are cosmic-ray counting tubes, *L* is a lead filter for removing shower particles, and *C* is a Wilson cloud chamber which is in a magnetic field of 3500 gauss. The circuits were so arranged that the cloud chamber would be set off only if a particle passed through tubes 1, 2, and 3, but not 4. In this way only the tracks of particles near the end of their range were photographed.

Wilson cloud-chamber photographs of cosmic rays. Originally, these were regarded as due to protons, but Anderson and Neddermeyer[9] pointed out the importance of identifying the penetrating particles.

By applying the methods considered above, Street and Stevenson[18] and more recently others[16,19,20] have calculated the rest mass of these heavy particles, and have arrived at values ranging from 110 *m* to 350 *m*. Typical approximate results for individual tracks are:

Street and Stevenson	130 *m*
Nishina, Takeuchi and Ichimiya	200 *m*
Corson and Brode	250 *m*
Ehrenfest	200 *m*
Ruhlig and Crane	120 *m*
Neddermeyer and Anderson	240 *m*

Since the experimental errors involved are still large, these discrepancies do not necessarily indicate that more than one mass is represented here, although that possibility is not precluded.

SUMMARY

It should be pointed out that, although the evidence has been separated into two well-defined categories to facilitate presentation, these two lines of investigations are interrelated. Furthermore, they lead in general to concordant results, both indicating the existence of a new elementary particle with electronic charge and a mass intermediate between that of an ordinary electron and proton.

The mass is not yet certain, but if it is unique, the results thus far point to a rest mass of the order of magnitude of several hundred times the electronic mass. Several investigators, however, suggest the possibility that the rest mass of these particles is not unique, and even postulate quantum transitions of the rest mass.

One may therefore conclude that the list of elementary particles has been enhanced by the addition of a new member, the *barytron*, whose properties, however, remain to be determined by future investigations.

FIG. 10(b). Track of a heavy electron near the end of its range obtained by Street and Stevenson in 1937.

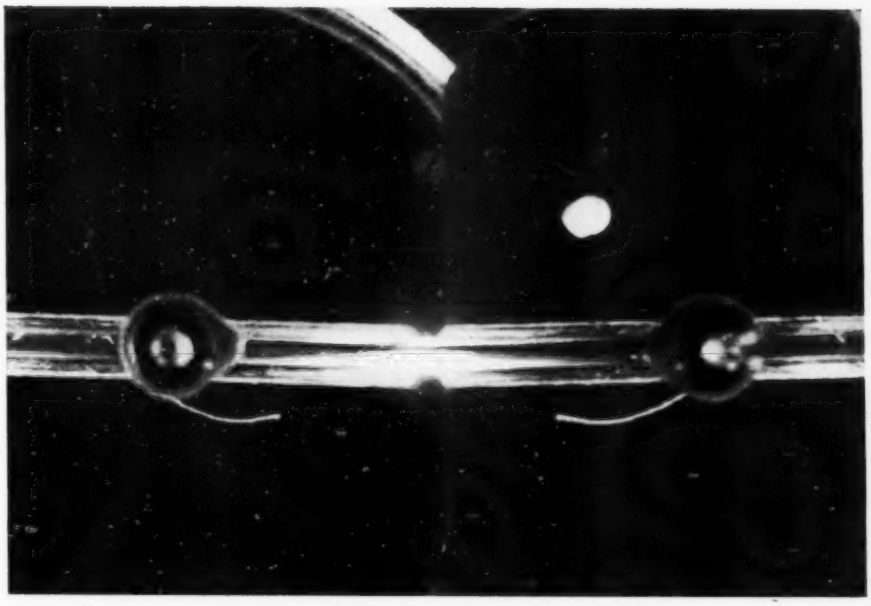


FIG. 11. A beautiful stereoscopic photograph made by S. E. Neddermeyer and C. D. Anderson of a Geiger-counter placed within a cloud chamber. A magnetic field is at right angles to the plane of the paper. The light track shown in the upper part of the picture is caused by a particle entering from above which passes through the glass walls and copper cylinder of the counter and produces the heavy track shown below the counter. Thus we see the path of a particle which enters at a tremendously high velocity and which actually comes to rest within the cloud chamber. From a measurement of the initial curvature of the particle and the thickness of matter traversed before it comes to rest a fairly accurate estimate of its mass can be made. From these data the mass appears to be about 240 electron masses. Other reasons exist for concluding that the track cannot possibly be caused by a particle of either electronic or protonic mass. The specific ionization in the upper track is too great to permit describing it to an *electron* having the energy indicated by the curvature of its path. Furthermore the specific ionization is less than 1/30 of that which would be caused by a *proton* having sufficient energy to produce the curvature shown. If the track produced after the particle has passed through the counter were caused by an electron its energy would be 7 Mev. An *electron* of this energy would produce ionization imperceptibly different from the usual high energy particle which produces a thin track and in addition it would have a range of at least 3,000 cm instead of the 1½ cm actually observed. On the other hand a *proton* having the track of the curvature shown would have an energy of only 25,000 ev and a range of less than 0.02 cm. One must conclude, therefore, that the mass is intermediate between that of a proton and that of an electron.

In conclusion, we wish to acknowledge the cooperation of The Bartol Research Foundation of the Franklin Institute, R. B. Brode, S. H. Neddermeyer and J. C. Street in providing pictures and diagrams included in this article. The authors are also indebted to Dr. Thomas H. Johnson and Professor G. P. Harnwell for many helpful discussions.

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Professor Arnold Sommerfeld

DECEMBER 5 is the seventieth birthday of Professor Arnold Sommerfeld of the University of Munich. Professor Sommerfeld has the reputation of being one of the foremost teachers of physicists in the world. A great number of our physicists of note have worked at one time or another with Professor Sommerfeld. In recognition of the large number of American physicists who have come under his influence, the December 1st issue of the *Physical Review* will commemorate his seventieth birthday by a collection of papers written entirely by physicists who have studied with him. In the table of contents of this issue we find the following names: Linus Pauling, W. V. Houston, A. Rubinowicz, Léon Brillouin, Otto Laporte, R. Peierls, G. Wentzel, W. Pauli, J. B. Green, B. Fried, E. U. Condon, F. London, Karl F. Herzfeld, Edward Teller, H. A. Bethe, W. Heitler, Carl Eckart, A. Landé, Philip M. Morse, Pearl J. Rubenstein, E. C. G. Stueckelberg, H. Froehlich, and P. P. Ewald.

Professor Arnold Sommerfeld was born December 5, 1868 at Königsberg, Germany. He studied mathematics and natural sciences at the University of Königsberg and in 1891 received the degree of Doctor of Philosophy. Four years later he became Privat-Dozent at the University of Göttingen. Here he came under the influence of Felix Klein who was then one of the strongest personalities in mathematical physics. After a stay of only two years, he became Professor of Mathematics at the Mining Academy of Claustal. In 1900 he was made Professor of Mechanics at the Institute of Technology of Aachen. After six years he was called away again and this time to one of the most important positions in Europe—the Head of the Department of Theoretical Physics in the University of Munich. Since then the prestige of Munich in the field of physics has risen enormously, and it has been the place where most of the younger theoretical physicists have obtained their start. Everyone who has been there speaks with great feeling and admiration for Professor Arnold Sommerfeld. He has received countless honors, and he is a member of a great number of technical societies. He is a member of the Academy of Sciences of Munich and a corresponding member of the Academies of Sciences in Berlin, Göttingen, Vienna and Upsala and Foreign Member of the Royal Society of London.

Professor Sommerfeld is perhaps best known for his research in the field of atomic structure. That he is just as active as ever is evidenced by the fact that *Science Abstracts* lists sixty of his papers in the last twenty years. However, in spite of his great renown in the field of atomic physics he has an entirely independent reputation in several fields of applied physics. In 1909 he published a fundamental paper on the propagation of radio waves on the earth, a paper which had enormous influence on the research in that field. This work was generalized by himself and by some of his pupils to apply to directed antennas. His last paper on this subject was published in 1926. In 1904 he published an epoch-making paper on the hydrodynamical theory of lubrication. That this theory was very successful and well-liked by the engineers is evidenced by the fact that it is presented in considerable detail in the well-known textbook

by Föppl, *Technische Mechanik* Volume 6, Number 71. He continued work on this field and published a paper on this subject only a few years ago. In 1909 he came out with another important paper on the stability of laminar flow in tubes and pipes, applying the method of small oscillations to the equations of hydrodynamics. His pupils in this field were, among others, Hopf and Heisenberg who both wrote dissertations extending Sommerfeld's work. There is also a long and beautiful paper on the breaking loads of beams.

Thus we see Arnold Sommerfeld as a teacher, an outstanding physicist in the field of atomic structure, and as one who has provided a fundamental background for many of the now very important fields of applied physics. Physicists everywhere join in celebrating his birthday and wishing him many returns of the day.

Here and There

Society of Rheology

The Society of Rheology will hold its next meeting on December 28 and 29, 1938 in Pittsburgh. Most of the sessions will be held at the Mellon Institute. A schedule of events follows:

December 28

A.M. 9–10	Registration
10–12:30	Technical sessions
P.M. 12:30–2	Luncheon
2–5	A Chemical Engineering Symposium. Joint session with the Industrial and Chemical Engineering Section of the American Chemical Society to be held in the Little Theater, Carnegie Institute of Technology
6:30	Dinner

December 29

A.M. 9–12	Technical sessions
12 M.	Luncheon followed by a business meeting

Dr. E. Ward Tillotson of the Mellon Institute is the chairman of the local committee and Mr. H. R. Lillie of Corning Glass Works is chairman of the program committee.

★

Sir William Bragg, President of the Royal Society, opened the Sir Robert Hadfield Metallurgical Laboratories of the Department of Applied Science of the University of Sheffield on September 14. The new extensions and improvements, which were built at a cost of £30,000, represent the first stage in a plan of development for which an appeal for £250,000 was made two years ago. Sir Robert Hadfield, chairman and managing director of Hadfield's Limited, Sheffield, gave £10,000 of the £30,000 required and equipped one of the research laboratories at a cost of £2,000. He also gave £5,000 for the plans of the new foundation.

Nature

New Appointments and Promotions

Dr. Viktor Francis Hess, formerly Professor of Experimental Physics at the University of Innsbruck, who in 1936 shared a Nobel prize for his work on cosmic rays with Dr. Carl David Anderson, of the California Institute of Technology, has joined the faculty of Fordham University.

★

Photoelasticity Conference

The eighth semi-annual meeting of the Eastern Photoelasticity Conference will be held on December 10th at Columbia University, New York City. A symposium on three-dimensional photoelasticity is planned for the technical sessions. Further information may be obtained by addressing R. D. Mindlin, Columbia University, New York City.

★

Science Clubs for Youths

Organization of science clubs on a nation-wide basis to coordinate the scientific pursuits of American youth was announced today by Mr. Robert T. Pollock, President of The American Institute of the City of New York. Plans for membership and detailed instructions for organizing and operating science clubs for young people from 12 to 18 are being sent today to youth leaders, teachers, and scientists throughout the country.

The new movement is an expansion of the Institute's already well-established science activities in New York City and vicinity, comprising at present 300 clubs with 6000 members. These clubs give life to the classroom science of young people by relating it to scientific research and giving the students opportunities for conducting independent laboratory projects. Science club members exhibit at the annual Science Fair and discuss current problems at the Science Congress.

George F. Baker Lectures

Dr. Harold C. Urey, Professor of Chemistry at Columbia University, will give the George F. Baker lectures in chemistry at Cornell University for the academic year 1938–1939 in November and December. Dr. G. B. Kistiakowsky, of the Department of Chemistry at Harvard University, will be Baker lecturer in February and March, and Dr. P. W. Bridgman, Professor of Physics at Harvard University, will lecture in April and May.

Science, October 14, 1938

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Professor Niels Bohr will be in Princeton during the spring term of this year (January 17–May 1) at the Institute for Advanced Study. He plans to give one formal lecture a week under the title "Elements and Principles of Atomic Theory."

★

Necrology

Dr. Arthur Stanley Mackenzie, from 1911 to 1931 President of Dalhousie University, died on October 2 at the age of seventy-three years. From 1891 to 1905 Dr. Mackenzie was Professor of Physics at Bryn Mawr College and was later for a short time head of the Department of Physics at Stevens Institute of Technology.

Some of the New Books

Service Books for Physicists

Demonstration Experiments in Physics. Edited by RICHARD MANLIFFE SUTTON. Pp. 545+viii; Figs. 408, 16×23 cm. McGraw-Hill Company, New York City, 1938. Price $4.50.

Procedures in Experimental Physics. JOHN STRONG AND COLLABORATORS. Pp. 642+x, Figs. 416, 16×23 cm. Prentice-Hall, Inc., New York City, 1938. Price $5.00.

Scientific Encyclopedia. D. Van Nostrand Company, Inc., New York City, 1938. 1234 pp. Price $10.

Physicists are particularly fortunate during the present year in that books telling how to make apparatus and to perform experiments are appearing. The first of the books listed above is a collection of nearly 1200 demonstration lecture experiments for the use of teachers of physics and general science. The book was prepared under the auspices of the American Association of Physics Teachers and includes contributions from two hundred physicists in one hundred thirty-one institutions. Emphasis in general has been placed upon the use of very simple apparatus and procedure. The book is divided into six parts covering each of the following divisions of physics: Mechanics, Wave Motion and Sound, Heat, Electricity and Magnetism, Light and Atomic and Electronic Physics. Each of these fields is covered in a uniform way so that lecture demonstrations are described for nearly every principle of physics. In the introduction it is stated that this book is very much like a "cook book" for those who need to demonstrate physical experiments. It seldom tells exactly how an experiment should be performed. It does not state whether a particular demonstration is exceptionally good or bad. It merely suggests a large number of ways in which a certain principle may be demonstrated and allows the person using the book to make his own choice. The book makes no attempt to provide working drawings for any of the experiments; however, many of the experiments are illustrated and with some ingenuity most of them can be duplicated. Physics teachers and others needing suggestions for demonstrations will find this book exceedingly useful. One might easily say that they have been waiting rather impatiently for it to appear. This book is so useful that it seems very ungenerous to offer any criticisms, yet the reviewer does not feel that the book is produced in as good a style in a mechanical way as some of the German books covering the same kind of material. For instance, the book is not nearly as attractive as those by R. W. Pohl which are published by Julius Springer. It is true, of course, that the German books are more expensive and perhaps one should hardly compare Dr. Sutton's book which sells at less than one cent a page with the German books which sell for two or three cents a page. The book is well indexed and serves its purpose very well.

The second book listed is a manual of procedures in experimental physics. The range covered in the book is evident from the table of contents which includes glass blowing, optical polishing and grinding, high vacuum technique, the use of fused silica, electrometers, Geiger counters, thermopiles, light sources and filters, photoelastic cells, amplifiers, photography, high temperature, research materials, construction and design, and molding and casting. In merely paging through the book one is immediately struck by the extraordinarily fine drawings and sketches. These sketches were prepared by Roger Hayward and they contribute enormously to the usefulness of the book. The drawings are usually in perspective and show every essential detail. One is pleased to see that the essential parts of each instrument are pointed out by the use of words such as "$\frac{5}{16}$-inch Shelby steel tubes" rather than by a letter and a reference to the text. Every part of each instrument is well labeled. It would be difficult to praise this book too highly. Its coverage of material is

excellent, the instructions are clear, and the book is beautifully manufactured. The author and collaborators and the publisher are to be congratulated in producing such a fine book.

The third book is not intended primarily for physicists. It is a scientific encyclopedia covering aeronautics, astronomy, botany, chemistry, engineering, geology, mathematics, medicine, mineralogy, navigation, physics and zoology. The contributing and consulting editors in the field of physics are LeRoy D. Weld, Erich Hausmann, and Edgar P. Slack. The book seems to have made a very good coverage of physical terms. For instance, if one opens the book at random he finds described within a few pages, mirage, mirrors and lenses, modulation, modulus of elasticity, molecular rays, molecular spectra, molybdenum and its properties, moment, moment coefficient, moment of inertia and momentum. Assuming the same density of coverage on the other pages, there seems to be no question but that most physics terms are included. When one looks at a particular topic such as molecular spectra one finds that the description is rather complete although in many places the English is poor. It seems to the reviewer that this book is a very useful one and on the whole seems to be very well produced.—E. H.

Mathematical Biophysics. N. RASHEVSKY. Pp. 340+xvii, Figs. 83. University of Chicago Press, Chicago, 1938. Price $4.00.

This book is primarily a presentation of the theoretical work which has been published by the author and his students during the past ten years. Professor Rashevsky takes as the goal of mathematical biophysics the derivation of all properties of various cells from a few fundamental postulates, and he vigorously defends his right to solve problems which are simpler than reality. The book will, however, be difficult reading for a biologist without considerable mathematical and physical experience, and it can scarcely be called an introduction to biology for the physicist.

In Part I fundamental concepts of physics are applied to an idealized living cell. The emphasis is placed on the diffusion of the substances consumed and produced by the reactions inside the cell, and the resultant mechanical forces. These ideas are then applied to nucleated cells and to cell aggregates. No one will question the operation of these physical principles in living cells, but there are not sufficient experimental data available to prove that these particular phenomena are as important as is predicted. Data on cell respiration are explained, but there are no independent determinations of the mechanism or the values of the constants which are chosen. It is more impressive that the conditions necessary and sufficient for a metabolizing cell to divide are fulfilled at about the diameter of an average cell. The predictions that cells having abnormally high glycolysis should divide rapidly and that rapidly dividing cells should be mutually repulsive agree with observations on cancer cells.

The electrical excitation of nerve and the conduction of the nerve impulse are considered in Part II. The various excitation phenomena are explained in terms of excitation and inhibition effects which are defined by two simultaneous differential equations. Although, in contrast to Part I, these equations are not the expressions of fundamental physical concepts, when they are introduced into the Kelvin cable equation a constant terminal velocity of the correct order of magnitude is predicted for the nerve impulse. In Part III the same type of excitation and inhibition analysis is considerably extended for application to the much more complex problems of the central nervous system. These lead finally to formulations of conditioned reflexes, *gestalt*-problems, and rational thinking and learning.

Undoubtedly experiments and further analysis will require numerous and perhaps extensive alterations of Professor Rashevsky's theories, but it seems probable that he has contributed to the foundations of biophysics and it is to be hoped that both biologists and physicists will be actively interested in this work.

KENNETH S. COLE
Columbia University

Combustion, Flames and Explosions of Gases. BERNARD LEWIS AND GUENTHER VON ELBE. Pp. 415+xiii, Figs. 79, 14×22 cm. Macmillan Company, New York City, 1938. Price $5.50.

In explanation of an underlying purpose the authors state in the preface: "The interest in combustion phenomena, shared alike by chemists, physicists and engineers, has led to a large number of investigations which vary widely in purpose and accomplishment as well as in disciplines of natural science on which they are based. There has been need of coordination and critical appraisal of the literature that has grown in volume and complexity. This the authors have attempted to do."

They further state, in explanation of a certain tendency: "To the question whether speculation, based on plausible interpretation of chemical and physical facts, is profitable, the authors answer that they believe in its value as a stimulant to further research. This, at any rate, has been the experience in the development of our sciences. Consequently, they have not hesitated to express rather definite views on a number of highly controversial subjects. It has been their endeavor to develop the reasons for these views as completely as possible in every case. They cannot emphasize too strongly that they welcome disagreement based on logical alternatives."

The subject matter under four main divisions has been subdivided into chapters and appendices as follows. Part I —Chemistry and kinetics of the reactions between fuel gases and oxygen. (1) Theoretical foundations, (2) The reaction between hydrogen and oxygen, (3) The reaction between carbon monoxide and oxygen, (4) The reaction between hydrocarbons and oxygen, (5) Emission spectra

and ionization in the flame front, (6) The problem of ignition by sparks. Part II—Propagation of flames. (7) Limits of self-propagation of flames (limits of inflammability), (8) The recording of flame movement and pressure development, (9) Spherical flames, (10) The influence of vessel shape and gas motion on flame propagation, (11) Stationary flames, (12) Theory of the burning velocity, (13) Diffusion flames, (14) Detonation, (15) Flames in electric fields. Part III—State of the burnt gas. (16) Thermodynamic functions of gases from band spectroscopy, (17) Explosions in spherical vessels with central ignition, (18) Freely expanding spherical flames, (19) Temperature and radiation of the burnt gas. Part IV—Problems in technical combustion processes. (20) Industrial heating, (21) Internal combustion engines. Appendix A—Data for thermochemical calculations, Appendix B—Limits of inflammability and Appendix C—Flame temperatures.

Much attention has been given to the type of reactions known as chain reactions, by means of which many processes are explained on consistent bases, and without which certain phenomena are unexplained; for instance, the transfer from a nonexplosive reaction in a hydrogen-oxygen mixture at 550°C at certain pressures, by mere lowering of the pressure, to an explosive reaction.

To the reviewer and to many other physicists presumably, hydrogen and oxygen have reacted to form water vapor in accord, looking apart from energy transfers, with the simple formula $2H_2+O_2 \rightleftharpoons 2H_2O$. It is therefore with much surprise that we find that those who work in the field described in this book find it necessary to give consideration to at least fourteen different types of elementary reactions. Of these some are "chain propagating" others "chain branching" still others "chain breaking." About half of the fourteen are thought to be of significance. Reactions between carbon monoxide and oxygen and between hydrocarbons and oxygen are found to be equally bound up in "chains."

The section on the propagation of flames is illustrated by numerous photographs, many of which were obtained by high speed photography. They have served in the determination of burning velocities and in checking theories of flame propagation.

The section on burnt gases is concerned with the thermodynamics of band spectra and its application to explosions in spherical vessels, their temperatures, pressures and dissociations. Here, as elsewhere in the book, a large amount of data is coordinated. The method of measurement of flame temperature by the "line reversal" method is described well. Many flame temperatures are reported.

The section on interval combustion engines treats of the common automobile-type, referred to as the Otto-type, and of the Diesel. Their indicator diagrams and plates showing thermal efficiencies as functions of compression ratio, and of the air content of the gasoline-air mixture are included.

The appendices are particularly fine.

That some points will need attention when a revision is considered is to be expected. To illustrate: (1) Since there are references to other portions of the book by chapter numbers, such chapter numbers at the top of each page would be appreciated. (2) Since one does not always desire to read a chapter or a book from the beginning when referring to it, a table at the beginning defining the symbols commonly used would be a great help. (3) Since tables and figures are the main source of precise data that are reported and of conclusions reached, the tables and figures should have sufficient explanatory matter in associated legends so that many of the essential facts may be gained by one with a reasonable background without his having to study over many pages of printed matter to obtain the meanings of the symbols and their general relation. Of course, the book cannot be written wholly as legends, but much more than has been can be so written profitably in this book. In Appendix C one wonders on what percentage basis combustibles are rated. Must the uninitiated read the book or the references to be certain? The authors have generally been quite careful regarding the use of units. A slip on p. 274 with regard to R may be noted. Whether for one mole or two moles, it is the same R.

The book contains a great amount of information which seems to be well explained and well coordinated. So far as the reviewer knows, it stands pretty much alone in its field. Despite the complaints which have been cited, the book well deserves very high respect. It will be much used.

A. G. WORTHING
University of Pittsburgh

Inventions and Their Management. A. K. BERLE AND L. S. DE CAMP. Pp. 733+xiv, Figs. 100, 14×22 cm. International Textbook Company, Scranton, Pennsylvania, 1937.

The authors of this book state in their preface that invention is a business and that he who would be successful must know the rules. This philosophy runs through the entire book. It is planned to help anyone who has something to do with inventions. It considers such things as the history of invention, procedure and records, the U. S. Patent Office, novelty and utility, selection of an attorney, patent drafting, promotion and sale and finally infringements. Each subject is illustrated by a case history. This book ought to be very helpful to physicists who ordinarily know so little about patents and their management. It remains to be mentioned that this book is very attractively printed and bound and contains a 36-page index.

Among Our Authors

Lennart Simons was born in Vörå, Finland, in September 1905. He received his training at the University of Helsingfors and has been assistant in the Laboratory for Applied Physics at the University of Helsingfors 1929–1938. Since that year he has been Lecturer of Applied Physics at the above institution.

Paul H. Schweitzer received the degree of Mechanical Engineer in 1917 from the Polytechnic Institute, Budapest, Hungary, and the degree of Doctor of Engineering from Polytechnic Institute, Dresden, Germany. In 1920 he came to this country and became engaged in commercial Diesel engine development. Since 1923 he has been associated with the Pennsylvania State College, where he is in charge of the Diesel engine laboratory.

Ellis I. Fulmer was graduated from Nebraska Wesleyan University in 1912, obtained his M.A. degree from the University of Nebraska in 1913 and his Ph.D. degree from the University of Toronto in 1919. In the period 1913 to 1919 he has served variously as chemist for the Agricultural Experiment Station, Nebraska; chemist-in-charge, Aetna Explosives Company, Quebec and chemist for the Central Experimental Farm, Ottawa, Canada. From 1919 to 1923 he was Assistant Professor of Agricultural Chemistry at Iowa State College. Since 1923 he has been Professor of Biophysical Chemistry at the same university.

Martin A. Pomerantz received his A.B. degree from Syracuse University in 1937, and his M.S. degree from the University of Pennsylvania in 1938. At present, he is research assistant at the Bartol Research Foundation of the Franklin Institute, and Scholar in Physics at the University of Pennsylvania.

Enos E. Witmer obtained his A.B. degree from Franklin and Marshall College in 1920 and his Ph.D. from the University of Pennsylvania in 1923. He held a National Research Fellowship at Harvard University from 1925 to 1927 and at the University of Goettingen during 1927–1928. He became Assistant Professor of Physics at the University of Pennsylvania in 1928.

John Covington Williams was born in Oxford, Ohio in 1911. He received the A.B. degree from Oberlin College in 1931 and his M.A. degree from the same institution in 1933. He obtained his Ph.D. degree at Iowa State College in 1937 with a major in biochemistry.

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Contributed Original Research

The Evaluation of Yield Value With the Sphere Viscometer

JOHN C. WILLIAMS AND ELLIS I. FULMER
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(Received July 25, 1938)

Various methods and formulas for determining yield value have been critically reviewed and a method is proposed for determining the yield value by means of the sphere viscometer.

KULAKOFF[9] compared the viscosities and yield values obtained for peat solutions by the use of three instruments, the capillary tube, the rotating cylinder and the moving sphere viscometers. Values determined with the first two instruments checked reasonably well with each other; but they did not agree with those from the sphere viscometer. Kulakoff stated that the poor showing of the latter was due to the following two factors. First, the method of Skrjabin,[16] which he employed, involves velocities for which the Stokes law equation does not apply. Second, the formulas for the calculation of yield value given by Schischtschenko and Baklanow[14] are approximate. It is the purpose of this communication to consider the method of calculation of the yield value from data obtained with the sphere viscometer.

The flow of a true liquid is represented by the equation

$$F = N dv/dx, \tag{1}$$

in which F is the shear force per unit area, N is the viscosity and dv/dx is the change of velocity with distance at right angles to the direction in which the force is applied. For plastic fluids, Bingham[3] proposed an analogous equation

$$F - f = N' dv/dx, \tag{2}$$

where N' is consistency, corresponding to viscosity and f is force per unit area, the yield value, which must be exceeded before motion occurs. Eq. (2) has not been integrated for the sphere viscometer as far as the present authors are aware. Buckingham[4] and others have carried out the integration for the capillary viscometer. In obtaining yield value with the capillary instrument, the volume extruded in unit time, Q, is plotted against the pressure applied per square centimeter, P. The resulting curve is extrapolated to zero Q and the yield pressure, P_a, so obtained is converted to yield value by the relation between pressure and shearing force at the wall of the capillary tube

$$f = P_a r/2l. \tag{3}$$

Here r is the radius of the capillary and l its length. The extrapolation is illustrated in Fig. 1. The equation of Buckingham shows that the curve bends towards the origin at low pressures;

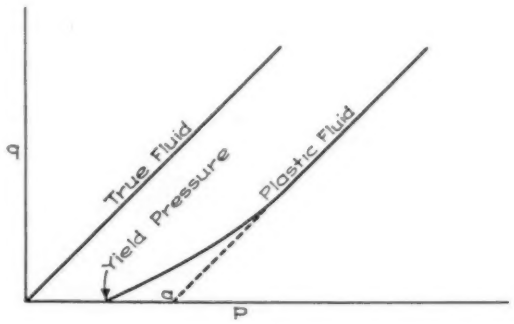

FIG. 1. The capillary viscometer.

so this method of obtaining yield values gives a first approximation rather than an exact determination.

Skrjabin[16] attempted to measure yield values of peat solutions with the sphere viscometer. A method somewhat analogous to that discussed for the capillary viscometer was employed. The velocities of various spheres of fixed radius, moving axially in a given cylinder, are plotted against difference in density between sphere and medium and an extrapolation made to zero velocity. The (d_2-d_1) intercept, Δ_0, in the notation of Kulakoff, is the difference in density which just causes the sphere to overcome the yield value; or, at this point Eq. (2) becomes

$$F=f. \tag{4}$$

The method of transforming Δ_0 to yield value will now be discussed. Lamb[11] has shown the shearing force, F, at the equator of a sphere moving through infinite medium to be

$$F=(\tfrac{3}{2})NV/r, \tag{5}$$

in which N is the viscosity, V, the velocity of the sphere and r, its radius. This equation has been employed by Phipps,[13] Barr[2] and De Waele[5] as well as in the method under discussion. The Stokes law equation may be written

$$(\tfrac{3}{2})NV/r=(\tfrac{1}{3})(d_2-d_1)gr, \tag{6}$$

in which g is the acceleration due to gravity. The conditions under which Eq. (6) applies have been discussed by a number of authors, e.g. Barr.[2] Combining Eqs. (5) and (6), the following equation is obtained:

$$F=((d_2-d_1)gr)/3. \tag{7}$$

As mentioned above, when (d_2-d_1) equals Δ_0, Eq. (4) applies, and Eq. (7) becomes

$$f=(\Delta_0 gr)/3. \tag{8}$$

This equation was proposed by Schischtschenko and Baklanow and employed by Skrjabin and Kulakoff.

On the assumption that a linear relation exists between V and (d_2-d_1) in a plastic fluid, as shown in Fig. (2), Skrjabin wrote Stokes law equation in the form

$$N=(2/9)((d_2-d_1-\Delta_0)gr_0^2)/V. \tag{9}$$

Kulakoff did not find this assumption valid, although there are reasons for considering his

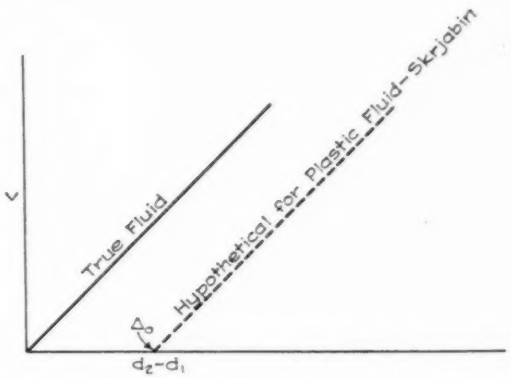

FIG. 2. The sphere viscometer.

results to be indecisive. Even if the relation is not linear, this does not invalidate the utility of the concept of Δ_0.

There are several objections to the formula of Schischtschenko and Baklanow, Eq. (8). The first of these was mentioned above, that Kulakoff found the yield values obtained to be out of line with those from the capillary and Couette viscometers. Kulakoff, however, worked at velocities above those for which the Stokes law equation applied. In the second place, the equation of Lamb gives the shear force only at the equator of the sphere, where it is a maximum, and in infinite medium. Finally Stokes law equation also does not apply except in infinite medium; if it is to be employed, it must be corrected for the wall effect.

The neglect of the wall correction is a serious error in a sphere viscometer of laboratory dimensions. Ladenburg[10] derived the following equation for the effect of the walls on the velocity of the sphere,

$$V(1+2.4r/R)=V_\infty, \tag{10}$$

in which R is the radius of the cylinder, V is the observed velocity and V_∞ is the velocity in infinite medium. A second equation for the effect of the ends of the tube was proposed; recent work by Bacon,[1] however, shows that the influence of the

ends may be neglected if the sphere is timed over the middle third of the cylinder. Eq. (10) has been shown to fail for values of r/R greater than 0.1. Empirical equations to cover a greater range have been proposed by Sheppard,[15] Suge,[17] Barr,[2] Francis,[7] and Fulmer and Williams.[8] Faxen[6] from theoretical considerations derived the equation

$$f_w = 1 - 2.104(r/R) + 2.09(r/R)^3 - 0.95(r/R)^5, \quad (11)$$

where f_w, the wall factor, is to be multiplied into the viscosity as calculated from the Stokes law equation. This equation applies when the following terms are negligible compared to unity, R_ϵ^2, $R_\epsilon(r/R)^2$, $(r/R)^6$ and $R_\epsilon^2(r/R)$. R_ϵ here represents the Reynolds number

$$R_\epsilon = (2vrd_1/N). \quad (12)$$

Eq. (11) has been verified over a wide range of viscosities by Bacon.[1]

It has been indicated that the maximum shearing force at the equator of the sphere, as calculated by Eq. (6), is not wholly applicable to the present problem. To test this equation, observations on the fall of a sphere in an anomalous liquid are needed. Such observations were made by Sheppard[15] with a nitrocellulose solution. His results, which have been recalculated employing Faxen's wall correction, are given in Table I. For ease in handling the data as presented, apparent viscosity calculated according to the Stokes-Faxen equation is taken as $f_w tr^2$ where t is the time of fall over the measured distance, the shear force as calculated by Lamb's equation is $f_w r$, etc. The apparent viscosity is shown plotted against shear force from Lamb's equation in Fig. 3. The

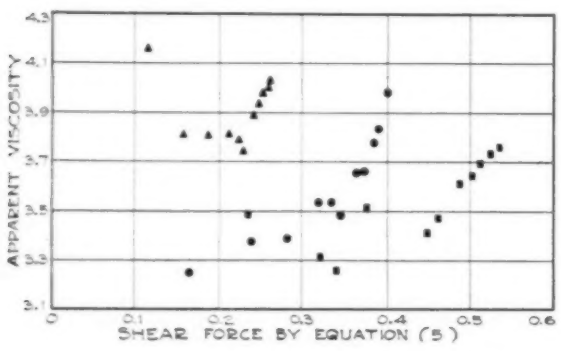

FIG. 3. A nitrocellulose solution, data from Sheppard.

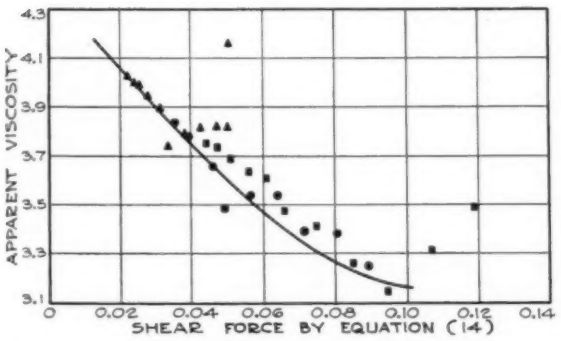

FIG. 4. A nitrocellulose solution, data from Sheppard.

spread of the points indicates that the true shear force has not been found.

Phipps[13] also found Lamb's equation to fail. Fig. 5, which demonstrates this, is reproduced from this author's paper. Only one sphere size was employed and the shear force was varied

TABLE I. *A nitrocellulose solution; data from Sheppard. In this table quantities proportional to viscosity and shear force are given.*

r/R	f_w	t	N	LAMB SHEAR FORCE	P. AND R. SHEAR FORCE
Fall distance = 19.5 cm; $r = 0.3170$					
0.33	0.375	110.5	4.16	0.119	0.0594
0.25	0.506	75.0	3.81	0.160	0.0535
0.20	0.596	63.6	3.81	0.189	0.0473
0.16	0.673	57.2	3.87	0.213	0.0427
0.14	0.710	53.1	3.79	0.225	0.0375
0.13	0.730	51.0	3.74	0.231	0.0331
0.11	0.772	50.1	3.89	0.244	0.0306
0.10	0.792	49.5	3.94	0.251	0.0279
0.091	0.810	48.9	3.98	0.257	0.0257
0.085	0.826	48.2	4.00	0.262	0.0238
0.077	0.840	47.8	4.03	0.266	0.0222
$r = 0.4762$					
0.33	0.375	38.2	3.25	0.169	0.0940
0.25	0.506	29.4	3.38	0.241	0.0804
0.20	0.596	25.1	3.39	0.284	0.0709
0.16	0.673	23.2	3.54	0.320	0.0641
0.14	0.710	22.0	3.54	0.338	0.0564
0.13	0.730	21.1	3.49	0.348	0.0497
0.11	0.772	20.9	3.66	0.368	0.0460
0.10	0.792	20.4	3.66	0.377	0.0460
0.091	0.810	20.6	3.78	0.386	0.0386
0.083	0.826	20.5	3.84	0.393	0.0358
0.077	0.840	20.4	3.89	0.400	0.0308
$r = 0.635$					
0.33	0.375	23.1	3.49	0.238	0.1190
0.25	0.506	16.2	3.31	0.321	0.1070
0.20	0.596	13.1	3.15	0.378	0.0946
0.16	0.673	12.0	3.26	0.427	0.0855
0.14	0.710	11.9	3.41	0.451	0.0752
0.13	0.730	11.8	3.47	0.464	0.0662
0.11	0.772	11.6	3.61	0.490	0.0613
0.10	0.793	11.4	3.64	0.503	0.0559
0.083	0.826	11.2	3.73	0.524	0.0477
0.077	0.840	11.1	3.76	0.534	0.0444

by changing the density of the sphere. The shear force indicated for the capillary tube was the maximum, at the walls of the capillary, calculated by Eq. (3).

Pasynskiĭ and Rabinovich[12] have proposed the following equation for the estimation of the velocity gradient in the sphere viscometer

$$dv/dx = V/(R-r). \quad (13)$$

They state, "In nitrocellulose solutions higher values are obtained by means of falling sphere than by the capillary method, yet it is possible to project both kinds of data on a common curve by disposing points according to their gradients of velocity." Eq. (13) may be transformed to terms of force by substituting in Eq. (1). This gives

$$F = Nv/(R-r). \quad (14)$$

The results of Sheppard are brought into agreement by employing Eq. (14) to calculate shear force; this is shown in Fig. 4. A re-examination of Phipps data* also confirms the statement of Pasynskiĭ and Rabinovich that it is possible to project data from the sphere and capillary viscometers on a common curve; this is demonstrated in Fig. 5.

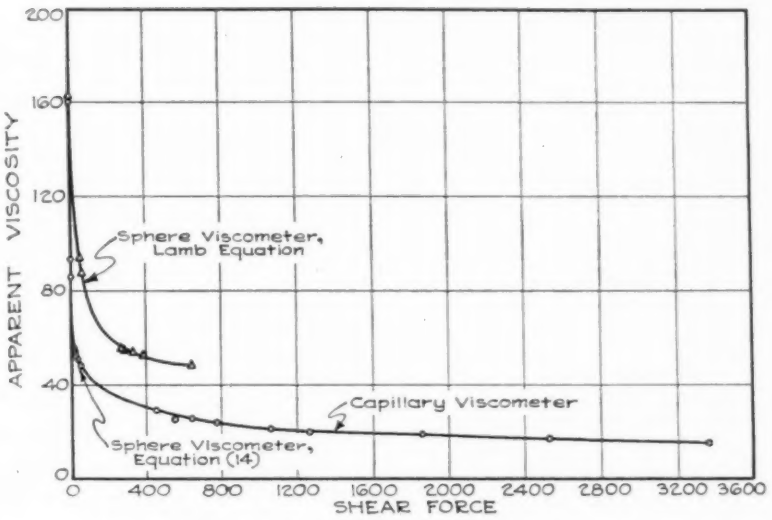

FIG. 5. Phipps data on cellulose acetate.

There are thus two lines of evidence on the validity of Eq. (14). The data of Sheppard show that the equation correctly represents the effect on the shear force of varying the radius of the sphere. The data of Phipps give presumptive evidence that the equation represents maximum shear force per unit area equivalent to that calculated by Eq. (3) for the capillary viscometer. (However, since the two portions of the corrected curve in Fig. 5 no longer overlap, it is not possible to say that exact equivalence has been established.)

It is now possible to calculate yield values from data obtained from the sphere viscometer. Several points in regard to this calculation must be kept in mind. First, in media where deviation from true fluidity is great, Eqs. (3) and (14) will undoubtedly give divergent values. Second, since the shear force in the sphere viscometer is much less, in general, than that at which the capillary viscometer is conveniently operated, the method of determining a first approximation to the yield value with the capillary, which was described above, will give a higher yield value than that obtained with the sphere viscometer. Finally the restrictions in regard to Reynolds number imposed by the Stokes-Faxen equation must be taken into account.

Combining the Stokes law equation and the

* *Note on the recalculation of Phipps data.* Numerical data were not given by Phipps and the following values were read from the curve presented.

Sphere	N	Shear force (Lamb)	Recalculated values	
			N	Shear force (P. & R.)
$R=1.500$ cm; $r=0.1587$ cm				
Bakelite	162	10	160	0.79
Ivory	94	40	93	3.16
Glass	87	50	86	3.94
Tin	56	260	55	20.50
Steel	55	280	54	22.10
Copper	54	310	53	24.40
Silver	53	390	52	31.60
Tantalum	49	640	48	50.50

To eliminate the Ladenburg correction (wall and end) and substitute the Faxen correction, viscosity values are multiplied by 0.986. To change shear force calculated by the Lamb equation to that given by Eq. (14), since $NV/(R-r) = 3NV/2r(r/(R-r)\cdot\frac{2}{3})$, all shear force values must be multiplied by 0.079.

Faxen wall correction with Eq. (14), the following expression is obtained.

$$F=(2/9)((d_2-d_1)gr^2f_w/(R-r)), \qquad (15)$$

when (d_2-d_1) equals Δ_0, $F=f$, as in the previous derivation. Therefore

$$f=(2/9)gr^2\Delta_0 f_w/(R-r). \qquad (16)$$

It was intended to consider the results of Kulakoff in terms of Eq. (16). Computation of the Reynolds number involved in the determinations shows, however, that neither the Stokes or Oseen equation is applicable.

In summary, a method has been proposed for the determination of yield value using the sphere viscometer. The procedure is briefly as follows. The velocity of fall, V, of spheres of identical radius but differing density is determined in cylinders of identical radius. The values of V are plotted against values of (d_2-d_1). The resulting graph is extrapolated to zero velocity. This intercept is designated as Δ_0 and is transformed into yield value by means of Eq. (16).

The authors wish to acknowledge receiving a number of references from E. C. Bingham.

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Clean-Up and Pressure Effects in Low Pressure Mercury Vapor Discharges: A Reversible Electrical Clean-Up of Mercury

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(Received May 21, 1938)

Studies with the ionization gauge reveal that in a positive column discharge in Hg vapor at low pressure there occurs a type of reversible electrical clean-up in which, under equilibrium conditions, a large and continuous exchange of Hg takes place between the space and the walls. The amount of Hg held temporarily in this way on the walls may be several times that in the gas phase. Thus if the current is suddenly stopped, the pressure may rise momentarily to several times its normal value; while if it is suddenly raised from a low value to a high one the lowering of the pressure may be so extreme as to cause surges across the arc or extinction of the arc (common occurrences during the starting of the Cooper Hewitt lamp). Evaporation from and condensation on free Hg surfaces, if these are at all limited in extent, are not rapid enough to prevent the effects. Electrophoretic and pressure effects are shown to be of great importance in these experiments. Thus in equilibrium, in a 2.1 cm tube, 1 m long, the pressure at the anode end was double that at the cathode end when the current was 2 amp. (mean pressure about 1 micron). This result is shown to be sufficiently accounted for by Langmuir's theory of the positive pressure effect. A method for calculating the drift speeds of ions and of the neutral gas in special cases is described. In the present case, a considerable drift of neutral gas is shown to take place under electron impacts towards the anode which compensates for the motion of the ions in the field. The initiation (due to clean-up) and phenomena of isolated surge regions in long tubes are discussed. These regions of aggravated low pressure which are usually situated toward the anode end of the tube, are plainly distinguishable by their relatively weak and reddish luminosity. Also the surges are evidenced by a sharp hissing noise which emanates mainly from the inductance. On suddenly stopping an arc in a tube at 185°C, the Hg which came off the wall spontaneously afterward appeared to have a mean life (τ) on the wall of about 4 min. τ did not appear to vary rapidly with the wall temperature nor did the amount of Hg (Q) so coming off. Q did not vary nearly as rapidly as the positive ion current to the walls. Assuming the clean-up to be due to these ions striking the walls, this and other more direct evidence indicate that Hg is dislodged by ions striking the walls as well as cleaned up thereby and that it is largely the balance between these two effects which determines the equilibrium amount of Hg held reversibly on the wall. The reversible clean-up here described is probably of considerable importance in all practical low pressure Hg discharge devices wherein rapid changes of current occur. In addition to this so-called reversible part of the clean-up, a much larger amount of cleaned up Hg was found which could only be recovered by heating. If the heating were carried out in stages, a quantity of Hg came off with each rise in temperature in such a way as to suggest that the Hg is held with varying degrees of binding. A clean-up on an iron surface was found similar to that on a glass or quartz surface. A tube containing unsaturated Hg vapor when strongly irradiated with the Hg resonance lines failed to show any clean-up from which it is inferred that the clean-up here described is not due to excited or metastable atoms. Careful tests with a McLeod gauge showed that gases other than Hg were not appreciably involved in the present experiments. The observations can be sufficiently accounted for on the tentative theory that ions penetrate into the walls to varying distances or to positions of varying stability, by virtue of their relatively high energies (15 volts or more), where they are held for greater or shorter lengths of time, according to their effective degrees of binding, until they escape as a result of random heat motions occurring either at the original wall temperature or at temperatures artificially elevated either in the oven or locally by ion bombardment.

THE gradual disappearance or clean-up of gas in a low pressure discharge tube and the possible recovery of at least part of this gas through the application of heat is well known.[1] In the present paper a clean-up in Hg vapor is described, part of which is reversible in character, and as a result of which there is a continuous exchange of Hg atoms[2] between the walls and the space.[3] In equilibrium an amount of Hg is built up on or in the walls by the action of the discharge such that under this action, Hg leaves the surface as fast as it is lodged there. The amount of Hg

[1] Summaries of many important papers on this subject will be found in books on high vacuum technique, of which may be mentioned those of S. Dushman, L. Dunoyer, F. H. Newman and G. W. C. Kaye. See also W. v. Meyeren, Zeits. f. Physik **84**, 531 (1933); **91**, 727 (1934).

[2] The Hg is thought of as going on the wall as ions, and coming off probably at least in large part as neutral atoms (see below).

[3] R. C. Mason, J. App. Phys. **9**, 131 (1938), has recently described the clean-up of Hg ions in an ionization gauge. His observations agree well with those here reported. (His reference 4, to my work, was meant to apply to the present paper.)

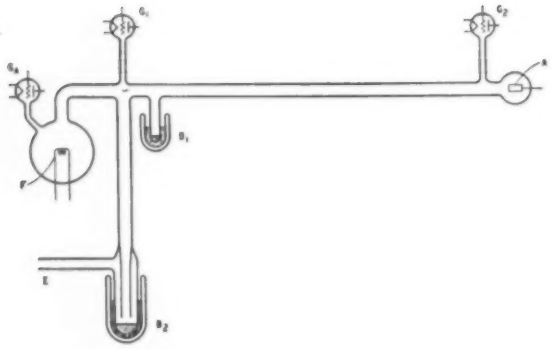

FIG. 1. Experimental tube. F: Cathode, A: Anode, G_A, G_1, G_2: Ionization gauges. B_1, B_2: Hg appendices. E: to liquid-air trap, McLeod gauge, Hg cut-off and pump. Distance between G_1 and G_2: 100 cm. Diameter of this section of tube: 2.1 cm o.d.

thus reversibly held on the surface may be many times that in the gas phase. As a result of this phenomenon, if the arc current is suddenly increased, a marked pressure reduction will take place before evaporation from free Hg surfaces can make good the loss; on the other hand if the current is suddenly decreased a marked increase in pressure will result due to Hg coming off the walls.

EXPERIMENTAL

It was shown in the previous paper[4a] that within a few hundredths of a second after a discharge of several amperes is started in a 2.5-cm arc tube containing only Hg vapor saturated at room temperature, the current decreases markedly and surges develop across the arc. In order to study the possible role of vapor pressure changes in these phenomena, the tube of Fig. 1 was constructed following lines suggested by Dr. K. T. Compton. Here ionization gauges of the Dushman-Found[4] type are placed as shown. $B1$ and $B2$ are Hg appendices which can be kept at any desired temperature. F is a 25 mil W spiral cathode and A a cylindrical Mo anode. The tube was well baked out under exhaust and the metal parts degassed.

In some experiments, the cathode bulb of 1 liter capacity was surrounded by a water bath to prevent undue heating and dislodgement of gas therefrom. The tube was kept under continuous exhaust at all times with a liquid-air trap between the tube and the pump. However, many careful tests were made with the tube closed off from the pump by a Hg cut-off with and without liquid air on the system and using a McLeod gauge which showed that the pressure effects to be described did not involve water vapor or any other gas except Hg vapor. The appendices were always kept at a temperature below that of the room in order to prevent any Hg from condensing in the tube.

During the experiment, a small "keep alive" arc of 20 milliamperes was usually kept running in the tube. When the current was suddenly increased to say 0.9 amp., a very marked pressure decrease (90 percent) was noted at the anode end as shown in Fig. 2, curve A.[5] At the same time a smaller decrease in pressure was noted at the cathode end of the tube as indicated by G_1 and G_A (Fig. 2, curves B and C). That the pressure did not drop as low at the cathode end of the

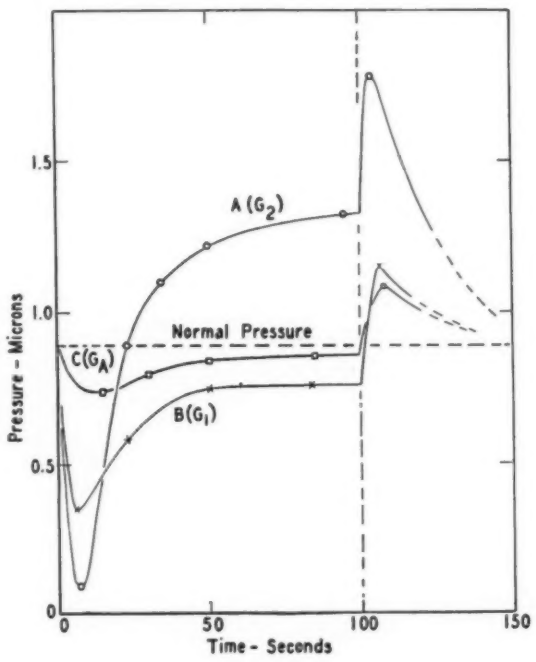

FIG. 2. Pressure in tube of Fig. 1 as a function of the time; A: at anode end. B: At cathode end. C: At cathode bulb. At time O, current is increased from 20 ma to 0.9 amp. At time 100 sec., current is reduced again to 20 ma. Appendix temperature 16.5°C (0.89 micron).

[4] S. Dushman and Clifton G. Found, Phys. Rev. **17**, 7 (1921).
[4a] Kenty, J. App. Phys. **9**, 705 (1938).

[5] Because of lag in the gauge, the true pressure drop was probably greater than indicated.

tube as at the anode end is reasonable since the appendix is at the cathode end.

In the case to which Fig. 2 refers, the arc current rose from 20 ma to an equilibrium value of 0.9 amp. in about 2 seconds. As the figures show the vapor pressure, after reaching a minimum 5 or 10 seconds after the current increase, gradually rose to equilibrium values which were quite different at the two ends of the tube.

At the cathode end this pressure was somewhat below normal, presumably due to a certain amount of more or less permanent clean-up which was taking place, probably mostly in the cathode bulb where the ion velocities were relatively high due to the large cathode drop. At the anode end the pressure reached an equilibrium value which was about twice normal. This pressure effect or electrophoresis will be discussed below.

After waiting about $1\frac{1}{2}$ minutes till the pressure had reached equilibrium, the current was reduced again suddenly to 20 ma whereupon the pressure in the tube rose quickly to a maximum (about 100 percent above normal at the anode end, Fig. 2, curve A) and then subsided to normal value. These effects can be explained if Hg vapor is cleaned upon the walls by the discharge only to be released again after the discharge is shut off.

The Positive Pressure Effect

The above experiment shows that if the tube is allowed to come to equilibrium, the pressure at the anode end is considerably higher than at the cathode end. This is a manifestation of the positive pressure effect discovered by Hamburger[6] and Skaupy[7] and of which the true explanation was given by Langmuir[8] and will be discussed below. A short study of this effect was made with the tube of Fig. 1. The results are shown in Fig. 3. Here the appendix was held at 12.5°C. Three minutes were allowed before each reading to allow equilibrium pressures to be attained. It is seen that the pressure difference is roughly proportional to the current in accord with the findings of other investigators. It is of interest, however, that in contrast to the low pressures here worked with most previous work on this effect has been done at pressures of the order of $\frac{1}{2}$ millimeter.[9] Even at a pressure of 0.18

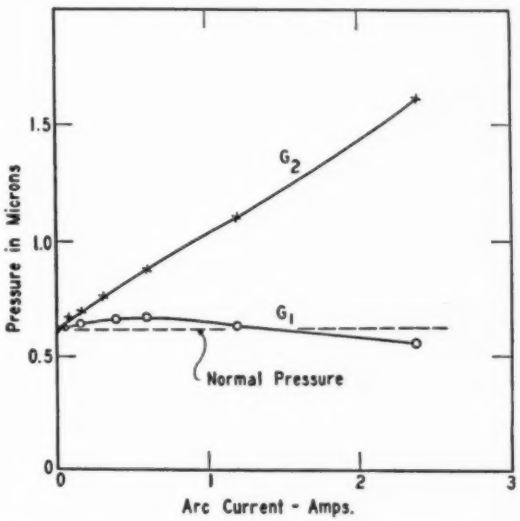

FIG. 3. Positive pressure effect. The curves show the equilibrium pressures at G_1 and G_2, Fig. 1, as a function of arc current.

micron (0°C) and with tube currents up to $\frac{1}{2}$ ampere a small positive pressure effect seemed to be present. Whether at still lower pressures (and possibly at much lower currents) the sign of the effect could be made to change and a steady negative pressure effect set up remains to be determined. A negative pressure effect was discovered by Stark[10] and further studied by Franck and Wehnelt.[11] Certainly a net drift of gaseous matter toward the cathode can be brought about but the effect is usually accompanied by voltage surges. Langmuir and Mott-Smith[12] found that the critical current density at which surges appear in a quartz capillary tube

[6] L. Hamburger, Proc. Amsterdam Soc. **20**, 1043 (1917).
[7] F. Skaupy, Verh. d. D. Phys. Ges. **19**, 264 (1917). For additional work on the subject see A. Rüttenauer, Zeits. f. Physik **10**, 269 (1922).
[8] I. Langmuir, J. Frank. Inst. **196**, 75 (1923).

[9] Druyvesteyn and Warmholtz, Phil. Mag. **17**, 1 (1934), have observed the effect in a Na vapor discharge at pressures of the same order as here used. They refer to such phenomena as electrophoretic effects.
[10] J. Stark, Boltzmann Festschrift, p. 399 (1904).
[11] A. Wehnelt and J. Franck, Verh. d. D. Phys. Ges. **12**, 444 (1910).
[12] I. Langmuir and H. M. Mott-Smith, Gen. Elec. Rev. **27**, 762, 770 (1924).

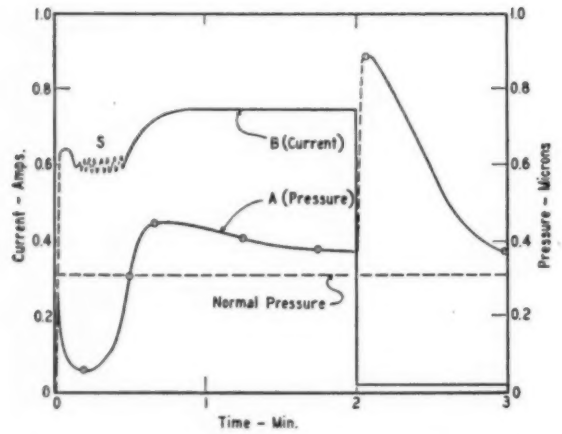

FIG. 4. Surge and pressure effects in tube of Fig. 1. At time O, current is raised from 15 ma to 0.65 amp. S: region of surges and low pressure. At time 2 min. current is again dropped to 20 ma. The pressure reading is that of G_2, Fig. 1 (anode end).

(0.232 cm i.d.) varies as the square of the pressure (in the range 1.2 to 12 microns).[13] They associated the surges with a degree of ionization approaching 100 percent.

SURGES

Figure 4, curve A, shows a case similar to Fig. 2, curve A, but with the appendix at 5.5°C. Here the current was suddenly raised from 20 ma to 0.65 amp. About 5 seconds after the current was raised, a marked hissing noise was heard which was found to emanate from the inductance in series with the arc. This was taken to indicate voltage surges across the tube, such as were described in the previous paper,[4a] in connection with the Cooper Hewitt lamp. The period of hiss lasted about 20 seconds which is seen by Fig. 4, curve A, to correspond with the period of low vapor pressure at the anode. As shown by Fig. 4, curve B, the arc current dropped somewhat during the "hiss" period to a slightly unsteady value. The initial maximum in this curve corresponds with the maximum in the curve of Fig. 10 of the foregoing paper,[4a] for the Cooper Hewitt lamp. The appearance of the anode end of the tube during the hiss period was characterized by a weak reddish and fluctuating light strikingly similar to that frequently observed toward the anode end of a Cooper Hewitt lamp when starting. This light is reddish because of higher series lines of Hg, as shown by the spectroscope; it indicates high electron velocities. Thus it was possible to "see" the region of very low pressure.

Without the inductance, the arc could be very easily extinguished at any of these appendix temperatures simply by suddenly increasing the arc current by raising the filament temperature.[14]

In regard to the surges which develop across a Cooper Hewitt lamp while starting (see Figs. 11 and 12 of the preceding paper[4a]), it was found that no surges whatever appeared when a resistance of 300 ohms was inserted at the anode to limit the current to a few tenths of an ampere. Evidently clean-up at such currents was not sufficient to lower greatly the pressure.

Comparison of Figs. 11, 12, 13, and 14, of the preceding paper,[4a] shows that in the case of Fig. 13, where the inductance was short-circuited near the beginning of the starting period the current, although very fluctuating, did not subsequently fall as low as in the other cases where the inductance was left in circuit. In the first case there are of course no voltage surges: the current can quickly adjust itself to whatever pressure conditions exist in the tube as was pointed out. But an inductance if present acts to prevent a decrease in current and thus aggravates a developing condition of low pressure, due to clean-up at high current, to the point where a surge region develops (see below).

CALCULATION OF THE POSITIVE PRESSURE EFFECT

According to Langmuir's theory, the positive pressure effect can be explained essentially as follows. The walls of the tube receive positive ions and electrons in equal numbers. The ions give up to the walls the momentum they have gained under the action of the electric field in the

[13] L. Tonks, Trans. Electrochem. Soc. **72**, 167 (1937), has given an admirable discussion of various causes which may operate in low pressure gas discharge apparatus to produce surges.

[14] The value to which the current could be jumped from 20 ma without putting the arc out, varied by a factor of 2 or more on different occasions (from 0.5 to 1 amp. at $T_A = 12.5$ C). This suggests that the behavior may depend on the initial state of saturation of the walls with Hg (see below).

direction of the cathode and likewise the electrons the momentum they have gained in the direction of the anode. But the momentum of the electrons is relatively negligible because of their small mass, and hence there is a resultant thrust on the walls in the direction of the cathode.

Meanwhile the electrons in the plasma are highly reflected elastically from the space charge sheath at the walls and through many collisions with the gaseous matter in the tube (atoms, and in the case of a high degree of ionization with the ions as well) communicate to the latter the momentum they gain in the field. To the same extent therefore (since ions and electrons are present in substantially equal numbers in the plasma) that the ions exert a differential thrust on the walls toward the cathode the electrons exert a differential thrust on the gaseous matter in the direction of the anode and a corresponding pressure gradient is set up.

If the atomic mean free path λ_a is such that $\lambda_a \ll D$ where D is the tube diameter, this electronic thrust is felt only near the wall and as a result a laminary flow of gas is further set up, toward the anode near the wall, and in the opposite direction in the central part of the tube.

In the present case, where $\lambda_a > D$ the ideas of Langmuir will be applied as follows. Also since no probe data were taken for the case of Fig. 3, the calculations will be made for an arc studied by Langmuir and Mott-Smith[15] for which complete probe data are available and for which the current density and vapor pressure were approximately the same as in the case of Fig. 3. In this case of Langmuir and Mott-Smith a 4-amp. arc flowed in a tube 3.2 cm in diameter in Hg vapor at a pressure of 1.1 bar (0.8 micron). The concentration of electrons n_e (taken to be equal to that of the positive ions n_p) as found by a cylindrical collector in the central part of the tube was 1.8×10^{11} cm^{-3}. On the other hand, in a practically identical case[16] a plane probe at the wall gave $n_e=1.0\times10^{11}$ cm^{-3}. Since n_e would be expected to be substantially smaller toward the wall,[17, 18] the value 1.3×10^{11} cm^{-3} will be here taken as a mean value across the tube. The gradient in the case in question was 0.24 volt cm^{-1}.

The electric force on the positive ions in unit length of tube will be

$$F_p=(\pi D^2/4)n_p eE$$

which with the above values of D and $n_p(=n_e)$, $e=4.77\times10^{-10}$ e.s.u. and $E=0.24/300$ e.s.u. gives $F_p=0.38$ dyne cm^{-1}. It will now be assumed that the ions on their way to the walls under the radial field,[17, 18] will make only a negligible number of collisions[19] and thus that this force is all communicated to the walls. It will also be assumed at first that a pressure gradient is set up which balances this entire force, thus that

$$(\pi D^2/4)dp/dx=0.38$$

from which $dp/dx=0.048$ bar cm^{-1}. Now in Fig. 3 at $1\frac{3}{4}$ amp. (corresponding to equal current density, assuming that dp/dx will be a function of the current density to a first approximation) the pressure difference across a 100 cm length of tube is seen to be 1.5 micron, giving $dp/dx=1.5\times(4/3)/100=0.02$ bar cm^{-1} (taking 1 bar $\leqq\frac{3}{4}$ micron) or less than half the calculated value. This pressure gradient would account for a force F_g per cm length of tube of $0.02\times\pi D^2/4=0.16$ dyne.

Calculation of Drift Velocities of Ions and of Neutral Gas

A further consideration will now be introduced which was left out of account by Langmuir and which, though not of great importance in the

[15] I. Langmuir and H. M. Mott-Smith, Gen. Elec. Rev. **27**, 762 (1924). Run 32, Table XIV.

[16] Langmuir and Mott-Smith, Gen. Elec. Rev. **27**, 538 (1924), Run 36-a, Table III. n_e was calculated from I_e and T_e as given according to $I_e=n_e e(kT_e/2\pi m_e)^{\frac{1}{2}}$.

[17] L. Tonks and I. Langmuir, Phys. Rev. **34**, 876 (1929)

[18] T. J. Killian, Phys. Rev. **35**, 1238 (1930).

[19] The mean free path of a Hg atom at 1.1 bar and (say) 100 C as calculated from viscosity measurements (Loeb, *Kinetic Theory of Gases*) is about 4 cm. An individual atom moving in the gas with an energy of the order of 1 volt, corresponding in speed to a Hg ion under the radial field (reference 17) would have a mean free path greater than this, first by a factor of $(2)^{\frac{1}{2}}$ on account of its high speed relative to the other atoms and second by a factor of 4 to 8 because of the Sutherland correction (see Carl Kenty, J. App. Phys. **9**, 53, 58 (1938) and references therein cited). Since little is known of the actual free path of an ion in its parent gas, it will be assumed, as is commonly done, that it is of the same order as that of a neutral atom. If so, an ion in the present case would only rarely collide with an atom on its way to the wall.

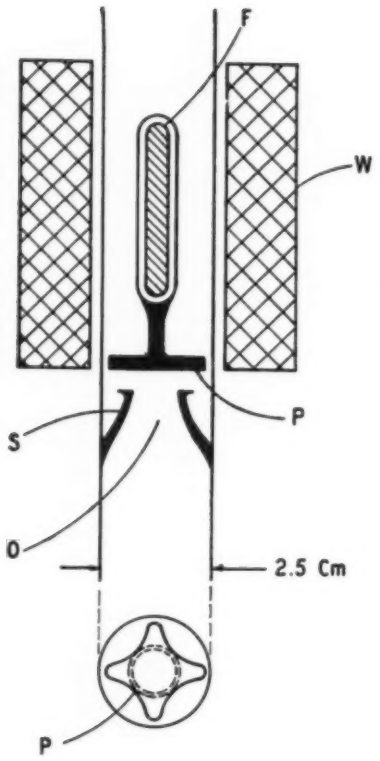

FIG. 5. Glass trap.

present case, must become of primary importance at much lower pressures, namely the mass transport by the ion drift toward the cathode.

In the case of Langmuir and Mott-Smith above cited,[16] the positive ion current to the wall, I_p, was found with the plane probe to be 1.1×10^{-3} amp. cm^{-2}. The mean life t of an ion before it reaches the wall will then be given by

$$\pi D^2 n_p e/4t=\pi D I_p$$

which, with the above average value of n_p, gives $t=1.5\times10^{-5}$ sec.

Under the axial field, in a time t an ion will acquire a component of velocity in the direction of the cathode of $t\times$axial acceleration and the average drift speed v_p of the ions will be half this. Thus

$$v_p=(1/2)(eE/m_p)t$$

which, with $m_p=3.3\times10^{-22}$ g and t and E as above, gives $v_p=8.7\times10^{3}$ cm sec.$^{-1}$ Now in equilibrium there can be no net transport of matter and hence neutral gas must stream at a speed v_a under electron impacts, toward the anode, at a rate which just balances the mass transport by ions. Thus

$$n_a v_a=n_p v_x.$$

Taking n_a as 2.2×10^{13} cm^{-3} at 1.1 bar pressure and (say) 100°C and n_p as 1.3×10^{11} as above it follows that $v_a=50$ cm sec.$^{-1}$

In accord with Knudsen's law,[20, 8] this flow will produce a frictional drag F_a on the walls of $\pi DRm_a v_a$ where R is the rate at which atoms strike unit area of the wall. Substituting the usual kinetic theory value for R it follows that

$$F_a=\pi D n_a(kT/2\pi m_a)^{\frac{1}{2}}m_a v_a$$

which, with the quantities as already given ($m_p=m_a$) and $T=400$°K, yields $F_a=0.02$ dyne cm^{-1} or about 5 percent of F_p.

The sum of F_g and F_a (0.16 and $0.02=0.18$ dyne) is seen to fall short of F_p by 0.2 dyne or roughly by 50 percent. Now certain observations led Langmuir to the view that due to some cause[21] the reflection of electrons from the wall sheath is not entirely specular and that as a result the combined thrust of ions and electrons yielded a force on the walls toward the anode of ϵF_p. If $F_g+F_a=\epsilon F_p$ in the present case then $\epsilon\leqq\frac{1}{2}$ (Langmuir used $\epsilon=0.3$).

Also if there were a large interaction between electrons and ions in the space, part of the pressure effect would be so neutralized in the space. While for the cases of very slow electrons, or a high degree of ionization, a large electron scattering could be thus caused, elementary calculations indicate that in the present case where $T_e\leqq25{,}000$°K[16] and the gas is about 0.6 percent ionized, the error in F_p (the ionic wall thrust) made by neglecting this effect will probably be of the order of less than a few percent.

Considering the large uncertainties in some of the factors mentioned, the present observed pressure effect could thus be said to be satisfactorily accounted for by Langmuir's theory.

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[20] S. Dushman, *High Vacuum* (1922).

[21] Langmuir (reference 8, p. 756) suggests statistical fluctuations of the positive ion space charge density in the sheath as a possible cause of the diffuseness of reflection. Other possible contributing factors which suggest themselves are (a) reflection of the electrons from the walls themselves (see reference 17) and (b) secondary electron emission from the walls if appreciable. Killian's results (reference 18, p. 1252) would, however, indicate the reflection to be more nearly specular.

The Initiation and Phenomena of Isolated Surge Regions

At pressures much less than those here considered, Tonks[13] has pointed out that because of their very long free paths the electrons will give up their momentum in a region other than that in which they gain it. In a tube of limited length they will for example give it up to the anode itself or to the anode end of the tube. In such a case there will be no motion of the neutral gas to neutralize the mass transport by ion drift and the gas will then be rapidly swept toward the cathode. In the case of a long tube a somewhat similar region could be set up locally for example by a clean-up which was relatively strong at that section. As already mentioned such regions are commonly seen in Cooper Hewitt lamps at starting. They are usually about a foot long and are located about a third of the way from the anode to the cathode.[22] Toward the anode end of such a region the gas would be thrust by the high speed electrons in the direction of the anode as Tonks[13] has pointed out. And toward the cathode end it would be drawn in the other direction through the ion drift as already described. The latter effect would be assisted by the impacts of ions on neutral gas provided the ratio of axial to radial field were large enough under these circumstances to allow the ions to make relatively long excursions down the tube.[19] These effects would appear to cause indefinite depletion of gas in the mid portion of such a region with the resultant open circuiting of the arc.[13] However the oscillograms of the preceding paper,[4a] and the prolonged hissing noise already mentioned indicate that arcs are frequently able to withstand long successions of voltage surges. (The larger the inductance in circuit the higher the surge voltage can be.) It would appear therefore that there is some mechanism associated with the condition of high surge voltage which replaces some gas in the tube and thus temporarily relieves the situation. Such a mechanism would be available if high speed ions striking the walls could dislodge cleaned up Hg with an efficiency greater than unity (see below).[23] Secondary electron emission from the walls at these high voltages could also allow the electrons to push on the walls rather than on the gas and thus allow the flow of gaseous matter at the anode end to change direction.

These surge regions are frequently observed to have relatively sharp boundaries indicating large density gradients at their ends.[24] Further, the boundaries are sometimes seen to fluctuate in position, giving evidence of the struggle of the density gradients with the electrical thrusts above discussed over the location of the boundaries. Ultimately the density gradients must win, as the Hg sources heat up, and the surge space closes up. This closing has been observed to take place more often from the cathode end, the boundary at this end being then the sharper.

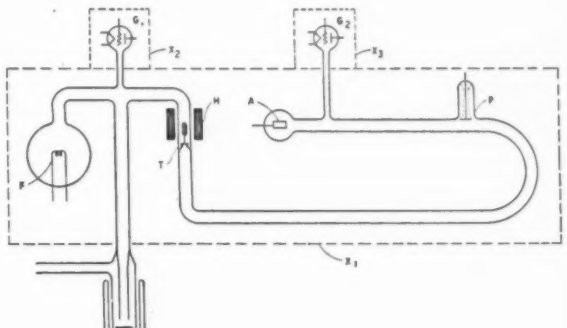

Fig. 6. Tube incorporating trap T (Fig. 5). P: Plane probe. G_1, G_2: Ionization gauges. x_1, x_2, x_3: Furnaces which can be run at separate temperatures. Tube diam.: 2.5 cm.

[22] The location, length and general behavior and appearance of these regions depend on the Hg pool temperature, the location of condensed Hg in the tube, if any, and on the state of the walls as regards saturation with cleaned up Hg. The last depends on the previous history of the tube: whether it was shut off when hot, how long it stood inactive, and whether any special heat treatments were performed, locally or otherwise. At low pool temperatures (0°C) the region usually appears to extend over the whole length of the tube, the current at no time rising very high (see preceding paper). At ordinary temperatures the region would not be expected to appear near the cathode end because of proximity to the source of Hg vapor.

[23] The first maximum in curve A, Fig. 4, indicated that the net amount of Hg cleaned up during the surge period due to over-all conditions is greater than if no surges were present. This is not incompatible with the present suggestion because the speed of the ions during an actual surge may be of a higher order than that between surges, the latter favoring a large clean-up. It was pointed out by Dr. Langmuir that the grazing nature of the ionic collisions with the walls during a surge may be an influencing factor. The maximum referred to is probably not due to Hg driven off the walls by rising wall temperature because curve A, Fig. 2, where no surges were present does not show such a maximum.

[24] At the negative end evidently a negative pressure effect might be said to exist.

The Recovery of Cleaned up Hg

The tube of Fig. 2 was unsuited to quantitative study. For instance in Fig. 2, the effects of the reversible clean-up are not nearly as marked as they would be if the gas did not flow in or out of the appendix to compensate for any pressure change taking place. Accordingly a mechanical trap, the details of which are shown in Fig. 5, was inserted into a Pyrex tube as shown[25] in Fig. 6. In Fig. 5, P is a quartz plate which rests on the seat S to close the orifice O. The surfaces P and S are ground plane. By means of the solenoid W acting on the iron cylinder F, the trap can be opened or closed.

Experiments with the tube of Fig. 6 were usually carried out as follows. At a certain appendix temperature T_A and with the trap open, an arc of some desired current was started in the tube and let run long enough (10 minutes) for equilibrium conditions to be well established. Then the trap was dropped which put out the arc and entrapped all the Hg beyond T, which was either in the gas phase or on the walls. Thereupon the pressure rose steadily as shown by the ionization gauge, due to the Hg coming off the walls. Fig. 7 shows the gauge reading as a function of the time, for three values of the arc current above mentioned.[26] The full lines show the actual readings and the dotted lines these readings as corrected for leakage through the trap.

These corrections were obtained in a calibration experiment in which, without any arc, and with the furnace surrounding the tube and gauges at the same temperatures as in the case of Fig. 7. T_A was kept at a value corresponding to several microns pressure for some minutes after which the trap was dropped and T_A lowered to 0°C. Gauge readings were then taken as a function of the time and the leakage of the trap thereby obtained as 0.014 micron per min. per micron difference in pressure on the two sides of the trap.

[25] In an earlier tube this trap was inserted between the appendix and the arc tube. When the trap was closed and the current was suddenly raised from a low value to a high value the pressure decreased tremendously throughout the tube and there was no building up of pressure again as in Fig. 2; rather the pressure continued to decrease till the arc went out.

[26] These currents were sufficiently small so as not to cause an appreciable positive pressure effect.

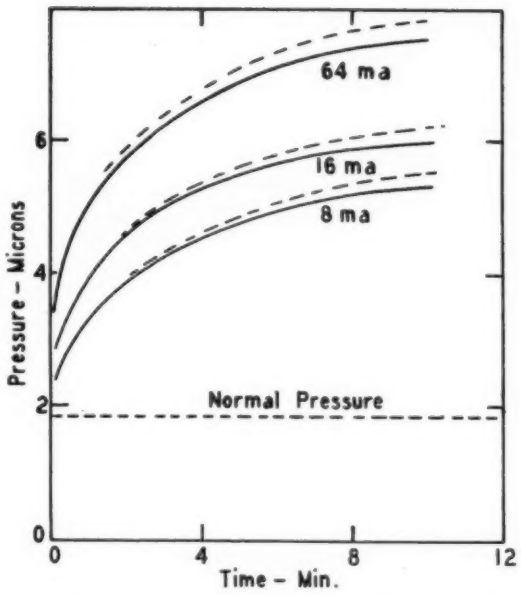

Fig. 7. Increase of pressure (G_2) in tube of Fig. 6, as a function of time after arc is shut off by closing trap. Appendix temperature 25.5°C (1.9 micron).

Before each experiment of Fig. 7, the tube was baked out under exhaust. The tube was kept under continuous exhaust. In the case of Fig. 7, the furnace surrounding the tube was kept at 185°C and the appendix at 25.5°C. The gauges were run at a constant temperature of the order of 60°C which was high enough to prevent any condensation.

Each curve of Fig. 7 shows the pressure rising toward a final value. The curves were found to be approximately exponential and such as could be explained if the atoms had a mean life on the walls of about 260 seconds, this value being the same for all the curves. The amount by which the final pressure exceeds the normal pressure may be taken to represent the amount of Hg, Q, reversibly lodged on the walls while the arc is running.

Measurements with the plane probe showed that the positive ion wall currents increased by a factor of 6 in Fig. 7, as the arc current increased from 8 ma to 64 ma. Assuming that the clean-up is due to ions striking the walls, the quantity Q is seen to increase far less rapidly than the ion current to the wall. It is necessary to assume either (1) that the wall has a limited capacity for retaining Hg or (2) that Hg is dislodged from the wall also by the ion bombardment. In the

latter case, the following equation could be set up for Q.

$$\frac{dQ}{dt}=AR-\frac{Q}{\tau}-BQR, \qquad (1)$$

where R is the rate at which ions are striking the wall, A represents the fraction of those striking which are retained, τ is the mean (undisturbed life on the wall of the cleaned up atoms) and B is a number which when multiplied by Q and R represents the rate at which cleaned up atoms are freed by ion bombardment. In equilibrium then

$$dQ/dt=0 \quad \text{and} \quad Q=AR/(1/\tau+BR). \qquad (2)$$

Thus Q would vary linearly at first with R but would gradually reach a constant value A/B independent of R. Also the higher R is, the quicker this equilibrium value will be attained. Such a variation is apparently found in the experiments.

The amount of Hg which came off the walls in the 8-ma case of Fig. 7, may be taken as 3.6 micron. The volume of the tube beyond the trap was about 500 cm³. At 185°C this gives $Q=3.8\times10^{16}$ atoms. Now the measured positive ion wall current in this case was 4.1×10^{-6} amp./cm² and the wall surface was about 600 cm² so that $R=4.1\times10^{-6}\times600/1.59\times10^{-19}=1.6\times10^{16}$ sec.$^{-1}$ Neglecting BR in comparison with $1/\tau$ in (2) and taking τ as 260 sec. a preliminary value of A of 0.011 is found. For the 64-ma case, the wall ion current was 25×10^{-16} amp./cm² and the amount of Hg cleaned up 5.9 micron, so that for this case $Q=6.1\times10^{16}$ and $R=9.4\times10^{16}$ sec.$^{-1}$ Then using $A=0.011$ and $\tau=260$ sec. for this case in (2) it is found that $B\leqq1.4\times10^{-19}$. Inserting now this value of B in (2) for the 8-ma case and solving, a better value of A is obtained, and so by the method of successive approximation it is found that $A=0.021$ and $B=3.2\times10^{19}$. Then in the 64-milliampere case BQR (Eq. (1)) $=18.4\times10^{14}$ sec.$^{-1}$ and $Q/\tau=2.3\times10^{14}$ sec.$^{-1}$ Thus here according to this theory 8 times as many atoms are dislodged per sec. by ion bombardment as come off spontaneously. Since in this case each little section of wall surface of area 4 square angstrom units is struck by an ion about once every 15 seconds, and the energy of the ions is quite high (of the order of 15 volts as shown by the wall probe floating potential with respect to space, or 100,000°K) it seems reasonable to suppose that local heating accompanying each ion impact could cause the dislodgement. Experiments to be described below show that cleaned up Hg atoms can be freed by heat and also by ion bombardment. On the present theory the observed reversible clean-up at the wall temperature used could therefore be explained if about one ion in 50 ($A=0.02$) striking the wall were so lodged there that it would remain on the average about 260 seconds if undisturbed, or would otherwise be freed by ion bonbardment according to the above value of B.

In experiments like those of Fig. 7, Q was found to be about the same, whether the arc were run for 10 minutes or for 3 minutes before closing the trap. Times less than 3 minutes could not be tried because of the fact that 0.1 mm Ne had to be let into the tube to get the arc started, and it required about this time to pump out all traces of the Ne. Tests with the McLeod gauge and Hg cut-off showed that the Q here measured was not appreciably due to Ne.

Experiments like those represented by the curves of Fig. 7 were carried out at oven temperatures from 50°C to 360°C. In all cases similar curves were obtained which indicated about the same value of τ and for similar arc currents the value of Q appeared to be about the same, increasing apparently slightly with temperature. This relative independence of τ on the temperature indicates that the atoms are not held by a simple work function type of force. It seems more likely that ions are driven into interstices (either natural or of their own making) among the glass atoms out of which they work themselves by their heat motions and those of the glass atoms. In order to explain the relative constancy of τ and Q, it would seem to be necessary to infer that they are driven in further the higher the wall temperature.

In order to study the possible effect of clean-up on the anodes in these experiments, the tube of Fig. 6 was partly rebuilt as shown in Fig. 8. Here A_1 and A_2 are two similar Mo anodes which could be heated to a bright red by radiation from W filaments inside. A_2 is approximately twice as far from the glass trap as A_1. The large bulb B (2000 cm³) is for the purpose of greatly

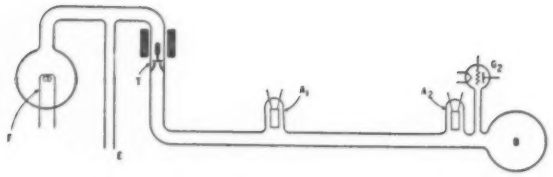

FIG. 8. Tube of Fig. 6 as rebuilt to detect clean-up on the anodes. A_1 and A_2: Similar Mo anodes which could be internally heated.

reducing the final value to which the pressure builds up after closing the trap. The effect of leakage through the trap was thus reduced to a very small value while increases of pressure (Q) were still large enough for convenient measurement. The arrangement also had the advantage that the experiment could be carried out at a much lower oven temperature without fear of condensation on the glass. It was found that all other variables being held as nearly as possible constant, Q was the same whether the anodes were run at a low temperature or at a bright red heat. Further, Q was within limits of error, twice as great when the arc was run to A_2 as when it was run to A_1, other conditions being the same. It was concluded therefore that the clean-up was associated only with the tube walls.

THE CLEAN-UP ON AN IRON SURFACE

Figure 9 shows an apparatus with which a preliminary study was made of the clean-up on an iron surface. Here G_1 is an ionization gauge of small volume. G_2 is essentially also an ionization gauge having an iron cylinder for collecting positive ions consideraly larger than the Mo cylinder of G_1. The cylinders are both closed as far as possible so that very few positive ions can strike the glass walls. The total volume of the system is about 35 cm³. After thoroughly baking out the tube under exhaust and degassing the metal parts, the tube was sealed off containing Hg vapor only, saturated at 22°C. G_1 was then used to measure pressure while the clean-up was made to take place in G_2. Positive ion currents of the order of 15×10^{-6} amp. were used in G_1 while similar currents of 1 ma or more were used in G_2. When the accelerating voltage (135 v) was suddenly thrown on in G_2 so that the Fe cylinder (at -22.5 v with respect to filament) was receiving 1 ma of positive ions, a pressure drop of the order of 50 percent was noted in G_1. The pressure reached an apparently steady low value. When the accelerating voltage in G_2 was cut off, stopping all ionization, the pressure in the system built up toward it's former value, apparently in an exponential fashion corresponding to an average life of the Hg atoms on the Fe surface of the order of one minute. This life as well as the magnitude of the clean-up appeared surprisingly independent of the temperature of the cylinder, which could be altered by running a variable input to the spiral anode. Since the general aspects of the clean-up on an iron surface[27] are similar to those in the case of a glass surface it seems reasonable to suppose that the mechanism of clean-up is essentially the same in both cases and that it is not one of Hg ions being held by electrostatic forces.

RECOVERY OF FURTHER MERCURY BY HEAT

Experiments showed that in addition to the Hg cleaned up in the reversible manner so far described there is also a much larger amount of Hg cleaned up which can only be recovered by

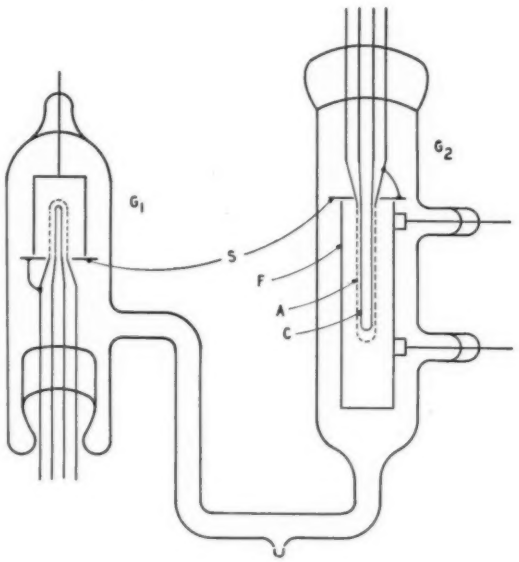

FIG. 9. Apparatus for study of the clean-up of Hg on an iron surface. F: Fe cylinder for collecting ions. A: W anode (in the form of a double helix). C: W hairpin cathode. G_1: Ionization gauge. S: Shields to minimize the number of ions reaching the glass.

[27] H. Alterthum and A. Lompe, Zeits. f. tech. Physik **17**, 407 (1936), observed a large clean-up of Ne (and also He and A) in Fe cathodes in a glow discharge tube which they attributed to ions being driven into the metal.

heating. The tube of Fig. 8 was rebuilt by substituting a simple quartz tube on the right of the trap and an all quartz trap for the glass one shown, this being sealed to the remainder of the tube by means of a graded seal. The internal diameter of the quartz tube was 1.7 cm and it's length 60 cm. With an ionization gauge the total volume on the right of the trap was 212.4 cm^3 and the surface exposed to the discharge was 325 cm^2. This tube was baked out under exhaust at 450°C and the metal parts degassed as usual.

Figure 10 shows an example of the type of experiment carried out with this apparatus. Here, with the tube in a furnace at 55°C, and with the appendix at 21°C a 20-ma arc was run for 10 minutes. At time 0 in the figure, the trap was closed, thus putting the arc out. Thereafter the pressure rose and descended as shown. After 8 minutes the input to the furnace was increased and the temperature then increased as indicated. Likewise the pressure rose to a high peak and then decreased as indicated. The average rate of leakage of this trap was measured at 55°C as 0.21 micron per minute per micron difference in pressure across it. Since the gauges were operated at constant temperature, being outside the furnace, and since at these pressures the atomic mean free path is greater than the tube diameter, the rate at which atoms leak through the trap should, for a given difference in the gauge readings on either side of the trap, be independent of the furnace temperature.[28] Therefore the amount of gas leaking through the trap in any given time expressed in microns in the tube at 55°C will be simply the product of the area between the curve and the normal pressure line (i.e., the line representing the pressure on the left of the trap) and the leak 0.21. Using a planimeter it was thus found that 2.5 microns came off spontaneously in the first 8 minutes and that 26 microns came off in the next 24 minutes under heating. In control tests, like that just described except that no discharge was operated in the tube before closing the trap, only an inappreciable amount of gas was developed. These showed that the gas as above measured was Hg cleaned up by the discharge.

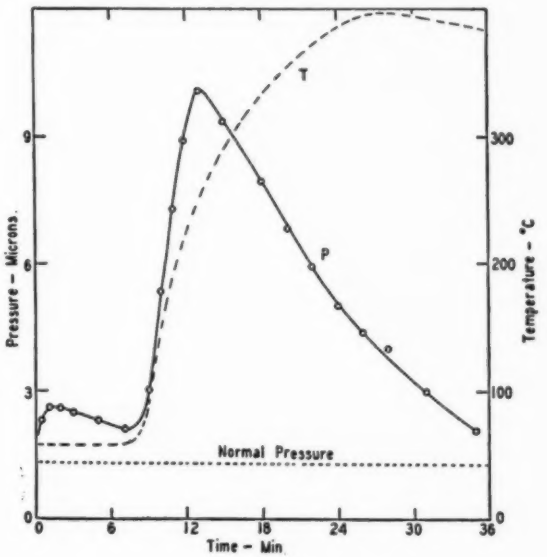

FIG. 10. Showing the relatively large amount of cleaned up Hg which can be driven off a quartz tube by heating. T: Furnace temperature. P: Pressure (reading of ionization gauge external to furnace).

Figure 11 shows a case entirely similar to that just described except that the temperature was raised in two stages as shown. The initial oven temperature was 63°C. It is seen that each increase in temperature dislodges a new amount of Hg, as if the cleaned up mercury were held with varying degrees of firmness. In one experiment, similar to that of Fig. 10, 19 hours were allowed to elapse (instead of 8 minutes as in Fig. 10) before the temperature was raised. But the amount of Hg recovered on raising the temperature from 55°C to 400°C was nearly the same as in the case of Fig. 10. Therefore heat is definitely necessary to dislodge most of the Hg. The results could probably be accounted for if cleaned up Hg were in effect held with different degrees of binding, possibly varying continuously upward from zero. The phenomenon is thus much too complicated to be handled by Eqs. (1) and (2); but these equations may be thought of as

[28] If N_g is the concentration of atoms in the gauge and n that in the tube it follows at these low pressures that $n = n_g(T_g/T)^{\frac{1}{2}}$ where T_g is the temperature of the gauge and T that of the tube. Now the rate at which atoms strike a surface (or a hole) will be proportional to $n(T)^{\frac{1}{2}}$ and therefore to $n_g(T_g)^{\frac{1}{2}}$. Also if the volume of the gauge is small compared with that of the tube, the amount of gas held on the right of the trap at any given gauge reading will be inversely proportional to $T^{\frac{1}{2}}$, therefore, for a given difference in gauge readings on the two sides of the trap, the rate of decrease of reading or "leak" as shown by the gauge reading on the right will be proportional to $(T)^{\frac{1}{2}}$. Measurements of the leak at 60° and at 365° confirmed this conclusion.

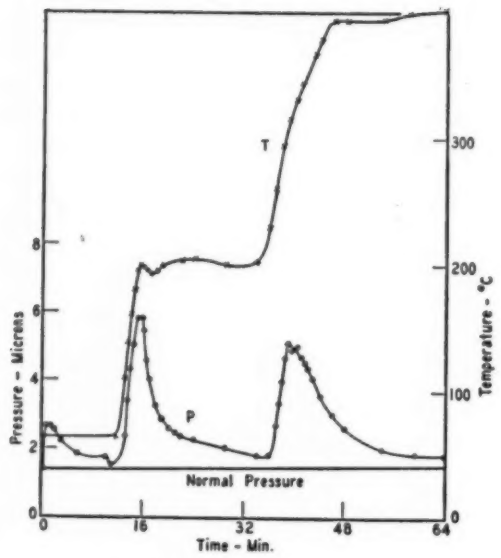

FIG. 11. Showing that Hg cleaned up on a quartz tube is held with varying degrees of binding.

applying within any small group of cleaned up Hg atoms having a given degree of binding.

That apparently only half as much Hg was recovered in the case of Fig. 11, as in the case of Fig. 10 may have been partly due to the fact that occasionally considerable variations in the trap leak were found, evidently depending on the manner of closing. This variability prevented accurate comparisons of the amount of Hg cleaned up under various circumstances with the present apparatus.

Taking the amount of Hg recovered in the experiment of Fig. 10 as 26 microns and the volume and surface of those parts of the tube involved as already given it is calculated that a total of at least 1.8×10^{17} atoms were cleaned up or 5.5×10^{14} per cm^2 of surface involved. This if the Hg were located all in one plane (which seems doubtful) would correspond to a layer of the order of $\frac{1}{2}$ atom deep (radius of the Hg atom taken as 1.8×10^{-8} cm). Other Hg may of course have been cleaned up which was not recovered at all. The possible connection between cleaned up Hg and blackening of the glass over long periods is not clear. Tolansky[29] found a discoloring of quartz in the case of high frequency discharges in Hg which he attributed to Hg driven into the surface.

[29] S. Tolansky, Proc. Phys. Soc. **42**, 556 (1930).

EXPERIMENTS WITH ARGON

Preliminary experiments with the previous apparatus indicated a clean-up of A by the discharge similar to that in Hg. The effects were much less striking, possibly because of the fact that much higher total pressures had to be used for operating the discharge (10 microns as compared with 1 micron in Hg). Also by first saturating the walls with A by a discharge in this gas (having frozen out the Hg), and then by operating a weak Hg discharge, definite evidence was obtained that cleaned up A atoms could be dislodged by the Hg ion bombardment. An inverse type of experiment also indicated that cleaned up Hg atoms could be dislodged by A ion bombardment.

TEST FOR POSSIBLE CLEAN-UP OF EXCITED ATOMS

A quartz tube containing Hg vapor and having an ionization gauge connected to it was strongly irradiated with the full radiation from a quartz Hg lamp close by. Both tubes were 2.1 cm in diameter and 40 cm long and were separated by a space of $\frac{1}{2}$ cm. The irradiating tube was filled with 3 millimeters of A and a drop of Hg and had oxide coated electrodes. A discharge of 1 amp. in this tube produced a strong odor of ozone and was otherwise known to be a strong source of the resonance lines of Hg. An elliptical Al reflector was placed around the tubes with these at the foci and a movable screen allowed exposure of the clean-up tube to the irradiation at will. Instead of sealing off the clean-up tube with a known unsaturated pressure of Hg vapor in it, it was connected by means of an adjustable capillary leak to an appendix, a liquid-air trap, and the pump. The ionization gauge used was of the nearly enclosed type of Fig. 9 which has a very small inherent rate of clean-up.

In carrying out an experiment the tube and gauge were first well baked out and the metal parts thoroughly degassed. Then with the Hg appendix at a known temperature the leak was adjusted to a minimum and gauge readings taken thereafter as a function of the time. These readings indicated a very slow rate of clean-up of Hg in the gauge. Then alternately over 5 minute intervals the tube was irradiated and cut

off from the radiation. Gauge readings were then plotted as a function of the time. Such experiments were carried out at appendix temperatures of 11°C and 22.5°C. At 11°C the pressure decreased smoothly at a diminishing rate by 20 percent over a 40 minute period, and at 22.5° by 3 percent in 25 minutes (the leak setting could have been different in the two cases). No consistent changes in slope could be detected at the times of starting or stopping the irradiation. It is estimated that a rate of clean-up 1/10,000 as great as that which occurred in the case of Fig. 2, curve *A*, could easily have been detected by this method. The effective strength of the resonance radiation bathing the atoms concerned in the two cases could scarcely have been different by many orders of magnitude and it seems safe to conclude tentatively that excited atoms and probably also metastable atoms were not appreciably involved in the present clean-up experiments.

Discussion

As a result of the reversible part of the clean-up here described it may be inferred that large changes in vapor pressure may follow whenever sudden changes occur in the current in a discharge of Hg vapor.

The effect was shown in the previous paper[4a] to be of great importance in the starting of the Cooper Hewitt lamp causing arc extinction and surges. It seems likely that it may also be of importance in the long anode arms of high voltage Hg rectifiers and other devices employing Hg vapor at low pressure.

There seems no reason to suppose that the reversible aspect of clean-up here found is peculiar to Hg alone. Rather it is probable that the relatively very low pressures at which discharges can be run with ease in Hg make this vapor peculiarly suitable for the observance of the effect.

The following tentative explanation of the clean-up, is put forward which seems to fit the observations sufficiently well: Ions penetrate into the glass (or other) surface to varying depths. In so doing they may make use of natural cracks or capillaries existing in the glass or by virtue of their relatively high energy—15 volts (1000,000°K) or more—they may push atoms of the crystal lattice aside and so penetrate. In the latter case the situation might be analogous to local melting and penetration with subsequent solidification and capture. The ability of the so imbedded ions (or atoms) to escape will depend on their stability of position with regard to their surrounding atoms (this includes the effect of depth and the possible sharing of chemical bonds), on their heat energies and on the random opening up, due to atomic vibrations, of the interstices in which they are lodged. The two latter factors will increase with the wall temperature. The important effect of ion bombardment in releasing cleaned up atoms[30] could probably largely be reduced to one of local heating. Such a mechanism of clean-up would seem to allow of a wide variation in the tenacity with which the cleaned up atoms are held, ranging from that in the case of what has been termed the reversible part of the clean-up to that in the case of the atoms which can only be recovered by extreme heating.

The preliminary experiments for the present investigation were carried out at Palmer Physical Laboratory, Princeton, in July 1929 and the work was continued over the following year and a half at the Laboratory of the General Electric Vapor Lamp Company. The experiments were discontinued because of pressure of other work.

I wish to express my thanks to Dr. K. T. Compton whose suggestions inspired this study, to Dr. R. D. Mailey and Dr. L. J. Buttolph of the General Electric Vapor Lamp Company for their constant interest and counsel, to Dr. I. Langmuir, Dr. A. W. Hull, Dr. S. Dushman and Dr. K. H. Kingdon, for valuable suggestions and to Dr. R. C. Mason whose continued interest in this problem has been an unfailing source of stimulation.

[30] The experiments of von Meyeren (reference 1) indicate that also bombardment by 800–900 volt electrons is able to release electrically cleaned up atoms of A and other gases.

A Geiger Counter for Beta-Rays

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(Received July 19, 1938)

A Geiger counter for beta-rays is described that is easy to construct and has the low background count of two per minute. Two modifications are in use, one in which the rays are admitted through an aluminum foil supported by a copper grid; and the other in which the material to be tested is placed directly within the chamber. The characteristics of various gases are discussed; it is shown that while organic vapors tend to lower the background count they also lower the sensitivity. A simple method for measuring the counter efficiency for rays of different energies is outlined.

CONSIDERABLE difficulty is experienced in the construction of a Geiger counter for measuring β-rays for a variety of reasons. The requirements that a counter has to meet are summarized as follows. First, to minimize its background count, the area in the horizontal section must be small. Second, to avoid the absorption of the β-particles, the wall must be thin or the material to be tested must be introduced directly into the counter itself. The first of these alternatives presents difficulties in construction and the second usually results in instability of operation. Third, the counter should subtend as large a solid angle as possible at the sample. Fourth, to avoid possible contamination the counter should not require reassembling to determine the background for each individual sample.

Various different designs of counters have been described in the literature.[1–4] Many of these have either too thick a window to transmit soft rays such as are emitted from rubidium or the background count is so high that the weak radiation, for example that of potassium, cannot be accurately determined. For statistical reasons, it is found impractical to measure a radiation whose count is less than that of the background.

A very simple counter has been developed at this laboratory which is easy to construct and which has been designed with the above qualifications in mind. Two modifications of the counter are in use, one with and the other without a thin aluminum window.

The window counter is more satisfactory for all rays except those of very low energy; it is illustrated in Fig. 1.

While the exact dimensions of the counter are not essential, a convenient size is that illustrated. The cathode is a thick-walled copper tube 2 inches long and $\frac{3}{4}$ inch inside diameter and the anode is a brass or nickel rod $\frac{1}{16}$ inch in diameter extending down the tube. The distance from the end of the rod to the side walls is from $\frac{1}{8}$ to $\frac{1}{4}$ inch less than that to the end of the tube. Both hard rubber and amber insulating plugs are equally satisfactory. The aluminum window is supported by a copper grid soldered to the end of the tube. A suitable grid can be made by drilling about 30 holes with a No. 40 drill through a 22-gauge copper sheet; the size of the holes is immaterial. The window, an aluminum foil 0.0003 inch in thickness, is waxed to the outer edge of the grid with a beeswax and resin mixture. A glycol-phthalate wax is preferable for the other

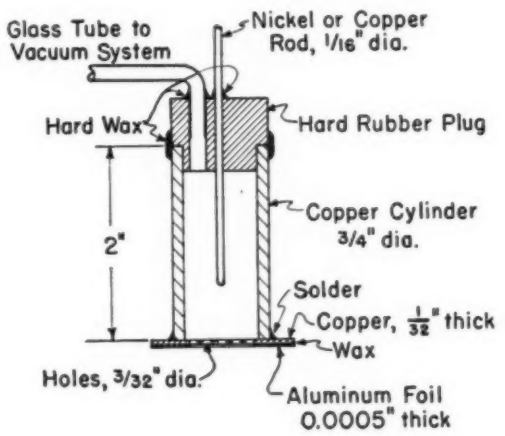

FIG. 1. Cross section of a Geiger counter for beta-rays.

[1] Hamblin and Johnson, Phil. Mag. **24**, 553 (1937).
[2] Halpern and Simpson, Rev. Sci. Inst. **8**, 172 (1937).
[3] Smythe and Hemmendinger, Phys. Rev. **51**, 178 (1937).
[4] Mühlhoff, Ann. d. Physik **7**, 205 (1930).

waxed joints, although any good sealing wax is suitable.

A modification of the counter to be used without a window is shown in Fig. 2.

A rotating disk of $3\frac{1}{2}$ inches in diameter will permit the testing of four samples at a single evacuation.

The primary precaution to be taken in the counter construction is the removal of points from the cylinder and rod by polishing with fine emery paper, followed by burnishing with a cloth. Dust can be washed from the rubber plug with alcohol.

A modification of the electrical circuit given by Johnson and Street[5] is suitable for amplifying the impulses, and a recorder made from a dollar watch and a telegraph relay is sufficiently fast for most radioactive materials.

In operation, the Geiger counter may be looked upon as a glow discharge tube where the applied potential is above the operating potential but below the breakdown potential for the cathode. A positive ion impinging on the cathode will lower the work function in its neighborhood sufficiently for a discharge to pass from the cathode to the anode.[6] These positive ions may be formed in the gas space by ionizing rays or they may come from the leakage of electricity from points in the tube. In order to lower the gradient in the neighborhood of the anode the $\frac{1}{16}$-inch rod was used in pace of the fine wire employed in the conventional counter.

Counters of the type illustrated when assembled without any appreciable care in polishing the various parts will have a background count of about 6 per minute for an applied voltage about 10 volts above the starting potential. When care is taken to burnish the anode and cathode the background can be reduced to about 2 per minute.[7] This is the limit obtainable due to cosmic rays.

Various gases have been tried in these counters with equal success. In practice from 1 to 1.5 cm of air has been found most convenient. At 1 cm of air the counter will operate on 720 volts. Argon and helium can be used at much lower voltages provided the counter is equipped with a liquid-air trap to freeze out the organic vapors; the presence of organic vapors tends to raise the operating voltage for both these gases but has no effect on air and hydrogen. Both the background and the efficiency *vs.* voltage curves give a plateau which is somewhat wider for hydrogen than for air; the actual efficiency, however, is lower. At 4.0

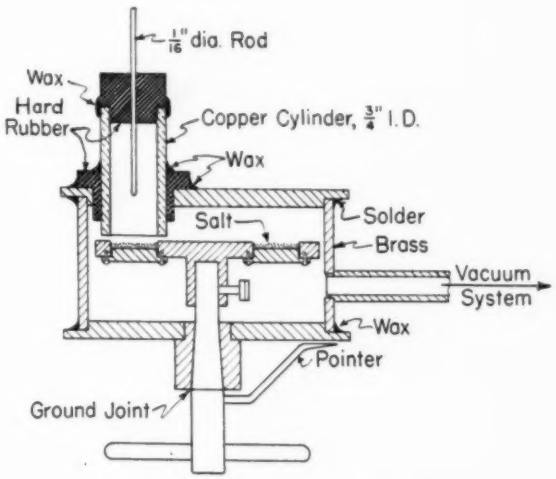

FIG. 2. Geiger counter without windows.

cm of hydrogen the counter will begin to operate at 900 volts, the background and efficiency remaining constant from 920 to 1030 volts. In contrast, air, which has a slightly greater efficiency at 1 cm pressure has a plateau of about 20 volts in width, above which the background rises slowly with voltage. Since the operating potential will remain constant provided there are no leaks in the system, the wdith of the plateau is not important.

The counter efficiency can be measured by means of a U_3O_8 standard. Standards can be easily prepared from ignited uranium nitrate, weighed as U_3O_8 and deposited lightly on a glass plate. UX_1 and UX_2 combined will emit 150 β-rays per 0.0001 g per min.; of these only 75 will have an upward component.

If the standard is placed directly below the counter, it follows from the geometry involved that only the small fraction of these 75 rays which have a nearly vertical component will be able to strike the counter window. In addition many of the rays that do strike the window will be absorbed in the aluminum or will fail to

[5] Johnson and Street, J. Frank. Inst. **215**, 293 (1933).
[6] A. Keith Brewer and J. W. Westhaver, J. App. Phys. **8**, 779 (1937).
[7] A. Bramley and A. Keith Brewer, Phys. Rev. **53**, 502 (1938).

ionize after entering the counting chamber. In consequence the counter efficiency is necessarily small, being of the order of 10 percent for most counters.

In converting the counter efficiency for uranium over to apply to any other source, it is necessary to know the energy of the different rays involved. The fraction of the rays striking the window will be the same for rays from any source placed in a definite position; on the other hand the absorption in the aluminum window will vary sharply with the energy of the rays, and the ionization within the counter will vary to a small extent.

The energy of the rays from a given source can be estimated by measuring the absorption coefficient, μ. This quantity is readily determined from the decrease in the number of counts when various thicknesses of aluminum are placed between the source and the window. The decrease in the number of counts (N) is found to obey the equation $N=N_0e^{-\mu t}$, where t is the thickness of aluminum expressed in centimeters.

The various factors determining the individual ray efficiency for UX_1 and UX_2 are given in Table I.

The percent transmitted given in column 4 is for an aluminum foil 0.002 cm in thickness. Column 5 gives the mean free path between ionizing collisions computed from the data of Williams and Terroux[8] for air at 1 cm pressure. In column 6 the effective length of the counter, 3 cm, is divided by the mean free path to give the number of mean free paths for a β-ray passing through the counter. Column 7 gives the number of positive ions formed per β-ray in the counter computed by the method given by Loeb.[9] The individual β-ray efficiency given in column 8 is the product of the probability of positive ion formation multiplied by the percent transmission.

A comparison of the present counter with those previously described will serve to illustrate the advantages of each. A typical counter with a thin wall (window) has been described by Hamblin and Johnson.[1] It is constructed from a Duralumin tube with a tungsten wire 0.045 mm in

TABLE I.

1 β-RAY SOURCE	2 MAX. ENERGY IN EV	3 μAl	4 PERCENT TRANS.	5 M.F.P. 1 CM	6 $\frac{L}{\text{M.F.P.}}$	7 $\frac{I^+}{\beta}$	8 EFFICIENCY PERCENT
UX_1	1.26×10^6	510	36	1.81	1.66	0.79	28.4
UX_2	2.3×10^6	14.4	97.2	3.04	0.986	0.63	61.4

diameter passing along the axis and suspended by means of an ebonite plug at each end. The Duralumin tubing, internal diameter 1.30 cm, is recessed in the middle to a wall thickness of 0.08 mm. The over-all length is 5.3 cm, while the window is 0.9 cm long and 3.7 cm² in area. Filled with dry air at 7.5 cm of Hg pressure, the background count is 5 per minute. This is comparable with that expected from the cosmic radiation. However, the thickness of the window is such that it practically excludes all β-particles with an energy less than 125,000 volts. For β-rays, whose energy is many times this value, this design of counter may be more efficient than the type described in the present paper, since the window subtends a much larger solid angle when the material is placed on a concentric cylinder surrounding the chamber. When only small amounts of material are available, however, the efficiency is materially lower. The difficulty involved in the construction of a counter of this type is much greater than that illustrated in Fig. 1.

The counter described by Mühlhoff is so designed that the sample to be tested can be placed directly within the chamber. This offers the advantage that a sample of 10 sq. cm can be exposed as compared with 2.5 sq. cm for the counter illustrated in Fig. 2. The background count of 27 per minute is rather high even considering the large area exposed; this high background works to a decided disadvantage when only a small sample is available. The main objection to the Mühlhoff design is that the background cannot be determined without dissembling the counter. It must also be borne in mind that when a foreign material is introduced into the counter itself it distorts the field, so that the characteristics become very sensitive to the position of the plate on which the sample is placed. Both the above objections are avoided in the design illustrated in Fig. 2.

[8] Williams and Terroux, Proc. Roy. Soc. **A126**, 289 (1930).

[9] Loeb, *Kinetic Theory of Gases* (McGraw-Hill, 1934), p. 45.

On the Symmetry of the Benzene Ring

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(Received June 1, 1938)

The values of the pulsation frequencies of C_6H_6 and C_6D_6 are calculated for trigonal and hexagonal symmetry, corresponding with the Kekulé and the centric formula, respectively. In the calculations it is assumed that the elastic forces for C−C, C=C linkages in the benzene ring equal these in open chains. In the centric model it is, moreover, assumed that the elastic forces between the C-atoms are equal to the average of the elastic force of the single and double bonds. The comparison of the experimentally observed Raman frequencies with the calculated shows that for the plane regular hexagonal structure we get a good agreement with the experimental values, while the Kekulé model gives much too low values. The frequency calculations decide also for the centric model.

THE question regarding the structure of benzene, i.e. the differentiation of the Kekulé and the centric formula, has not been dealt with successfully for a long time. The problem has become acute with the investigation of Raman effect.

The most essential difference between these models is that the Kekulé model has trigonal symmetry with alternating C−C and C=C linkages in the C_6-ring, while the centric model has hexagonal symmetry with $1\frac{1}{2}$-fold linkages between the carbon atoms.

Many scientists, among others Wood, Barnes, Brattain and above all Kohlrausch[1] have nowadays come to a decision on the centric model.

They have arrived at this solution above all on the basis of the polarization relations[2] of the benzene Raman lines and the number and intensity of these lines. But the calculation of the frequencies possible with these models also points in the same direction.

Starting from the knowledge of valency forces for the homopolar linkages C−C, C=C and C−H, that have been measured from the Raman spectra of saturated aliphatic hydrocarbons, I have endeavored to find a possibility for the comparison of the experimentally observed Raman spectra with a spectrum calculated for these models. Herein I have confined myself to the frequency of such an oscillation that with certainty is attributable to experimentally observed Raman line.

[1] K. W. F. Kohlrausch, Physik. Zeits. **37**, 58 (1936).
[2] L. Simons, Soc. Scient. Fenn., Comm. Phys.-Math. **6**, 13 (1932).

CALCULATION OF FREQUENCIES

Fortunately we know that the strongest Raman line 992 cm^{-1} of benzene is to be attributed to the symmetric contraction and dilatation of the C_6H_6-ring.[3] By this fundamental oscillation "the pulsation," the H-atoms oscillate in the same directions as the C-atoms. It is also proved that 3050 cm^{-1} belongs to an analogue symmetrical oscillation, by which however the C- and H-atoms move in opposite directions. The most important proofs of this attribution issue from the selection principles for the Raman effect, the experiments of polarization and from

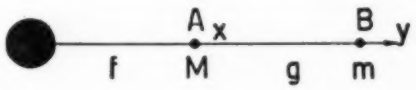

FIG. 1.

the conduct of the Raman frequencies by substitution.

In the calculations we suppose that the valency forces k, h, g for C−C, C=C, and C−H linkages, respectively, in the benzene-ring are equal to these in open chains.

CENTRIC MODEL

We suppose a plane regular hexagon with a C-atom of the mass m in each corner and the elastic force $\bar{k}$=average of the elastic force of the single and double bonds. Obviously the C-atoms have to move radially by the pulsations of this model. In order to obtain the value of

[3] L. Simons, Nordiska (19 skandinaviska) naturforskarmötet i Helsingfors 1936.

pulsation frequencies, we suppose that the C-atoms in the naked C-ring are connected with a fixed center by means of an elastic force f. The frequencies will then equal the frequencies of oscillations of the following linear model: an

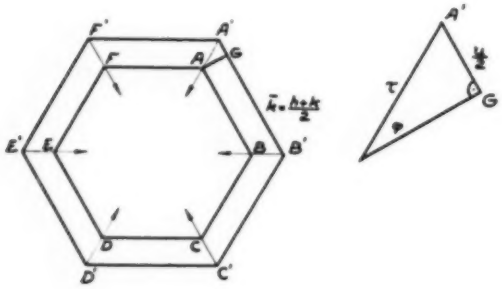

FIG. 2. (In the right figure the unmarked point of the triangle should be indicated as A.)

infinite mass connected with the C-atom by f, which again is connected with the H-atom by g (Fig. 1). Differential equation of the movement

$$Mx'' = -fx - gx + gy$$
$$my'' = gx - gy.$$

With substitution

$$x = Ae^{i\omega t}$$
$$y = Be^{i\omega t},$$

we get

$$(M\omega^2 - f - g)A + gB = 0$$
$$gA + (m\omega^2 - g)B.$$

Frequency ω comes from the equation

$$\begin{vmatrix} M\omega^2 - f - g & g \\ g & m\omega^2 - g \end{vmatrix} = 0.$$

Now the fictive elastic force has to be calculated, which is done as follows: When all the C-atoms A, B, etc. have moved a distance τ to the new positions A', B', etc. we obtain a new regular hexagon (Fig. 2). The sides AB, BC etc. are then elongated with a length μ. From the figure we get

$$\mu/2 = \tau \sin \varphi = \tau \sin 30° = \tau/2.$$

The work by the tension of the springs or the potential

$$V = 6 \cdot \bar{k}\mu^2/2 = 6 \cdot \bar{k}\tau^2/2.$$

If, on the other hand, the forces of the linear oscillators are called f, we get

$$V = 6 \cdot f \cdot \tau^2/2.$$

From this we get the valency force

$$f = \bar{k}.$$

THE KEKULÉ MODEL

In calculating the corresponding dilatation frequencies of the Kekulé Model we can also from the viewpoint of frequency substitute the C_6-ring by a C-atom, which is connected with an infinite mass by the elastic force f. The direction of the oscillation will not now be radial. We suppose that it coincides with the direction of the resultant of the moment forces. This is necessary if the oscillation is to be linear. This direction of the resultant is determined as follows (Fig. 3).

When all the C-atoms A, B, C, D, E, F are elongated a length τ to the new positions A', B', C', D', E', F', we get the equiangular but not equilateral hexagon $A'B'C'D'E'F'$. The sides AB, CD and EF are elongated with a length v, and the sides BC, DE and FA with a length u.

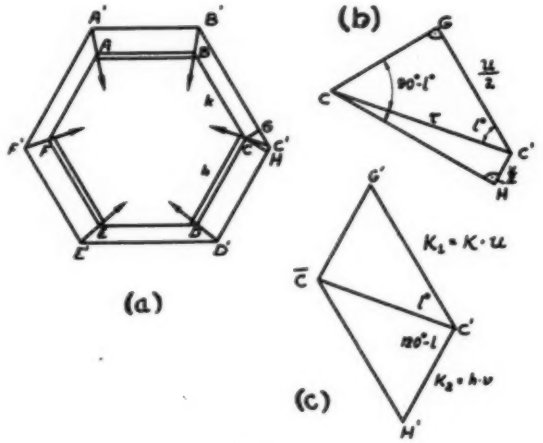

FIG. 3.

We call the direction force of the single bond k and of the double bond h. We call

$$q = h/k. \tag{1}$$

From Fig. 3(a) we get

$$u/2 = \tau \cos l$$
$$v/2 = \tau \sin (l - 30). \tag{2}$$

The force

$$K_1 = ku$$

works in point C' in the direction of $C'G$ and the force

$$K_2 = hv$$

in the direction $C'H$. From Fig. 3(c) we get

$$\frac{hv}{ku} = \frac{\sin l}{\sin (120 - l)}. \tag{3}$$

From Eqs. (1), (2) and (3) we get

$$\sqrt{3} \cot 2l = 1 - 2 \cdot 1/q.$$

The potential

$$V = 3ku^2/2 + 3hv^2/2,$$

on the other hand

$$V = 6 \cdot \tfrac{1}{2} \cdot f\tau^2,$$

whereof

$$2f = k(u/\tau)^2 + h(v/\tau)^2.$$

From Eqs. (1), (2) and (3) we get

$$f = k(1 + q - (1 - q + q^2)^{\frac{1}{2}}). \tag{4}$$

If an H- and a D-atom, respectively, are added, we suppose (and then we get a lower limit) that the H- and the D-atoms, respectively, oscillate in the resultant direction mentioned above. Thus we come to the same frequency formula as by the centric model, but here we must take the value (4) for f. On the other hand, if we suppose that H and D, respectively, do not lie in the direction of the resultant, we get a greater value. When the C-H and the C-D direction, respectively, is perpendicular to this direction we get an upper limit. By the substitution in the equation we use following values

$$M = \frac{12}{60.6 \cdot 10^{22}} g$$

$$m(H) = \frac{1.01}{60.6 \cdot 10^{22}} g, \quad m(D) = \frac{2}{60.6 \cdot 10^{22}} g$$

and the valency forces according to Hibben[4]

$$k = 4.40 \cdot 10^5 \text{ dyn-cm}^{-1}$$
$$h = 11.0 \cdot 10^5 \quad "$$
$$g = 5.02 \cdot 10^5 \quad "$$

and according to Kohlrausch[5]

$$k = 4.31 \cdot 10^5 \text{ dyn-cm}^{-1}$$
$$h = 9.36 \cdot 10^5 \quad "$$
$$g = 4.58 \cdot 10^5 \quad "$$

TABLE I.

Molecule	Calculated values: Kekulé model, trigonal symmetry: H, resp. D, fixedly connected with C	Calculated values: Kekulé model, trigonal symmetry: Unburdened ring oscillation (upper limit)	Calculated values: Kekulé model, trigonal symmetry: Movable masses in above-mentioned direction of resultant (lower limit)	Calculated values: Centric model, hexagonal symmetry: Movable masses in radial direction	Observed values
C_6H_6	873 (854)	909 (889)	869 (<854)	1000 (944)	992
C_6D_6	841 (823)	830 (889)	830 (<823)	951 (895)	944

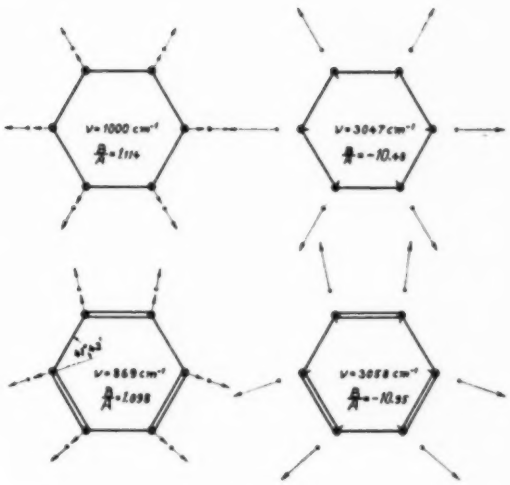

FIG. 4.

RESULTS

The calculation results for both C_6H_6 and C_6D_6 are given in Table I. The frequencies obtained with the Kohlrausch values are placed in parentheses. For purposes of comparison the experimentally measured frequencies are also given in the table.

In the next figure (Fig. 4) we see the received oscillation formula both for the centric and the Kekulé model. A indicates the oscillation amplitude of the C-atom and B that of the H-atom.

[4] J. H. Hibben, Chem. Rev. **18**, 7 (1936).
[5] K. W. F. Kohlrausch, *Der Smekal-Raman-effekt.* (1931), p. 154.

The relation B/A between these amplitudes is given for every form of oscillation, as well as the frequency. By the Kekulé model the oscillation direction forms an angle of 41° 42′ with the direction of the single linkage.

Discussion

It follows from Table I that in no case by using the Kekulé model we can obtain the experimental value 992 for the C_6H_6 pulsation, or by using the same force constants to 944 for C_6D_6. The real value of the Kekulé model pulsation frequency is smaller than the values that we get when we substitute 12 and 13 for m. For $m=12$ we get only 909, not to mention the case when $m=13$, when we get 873. Furthermore I would like to point out that k is chosen quite big, because this value gives the value 1120 for the pure C−C frequency, and in another way I have got a value = 1040 cm^{-1} for the same.[6] The influence of $q=h/k$ on the value of the frequencies is very small.

On the other hand, we get a good conformity with the experimental values for a centric model with $1\frac{1}{2}$-fold linkage forces both for C_6H_6 and C_6D_6, having the error limits of the force constants in view. It may be interesting to point out that the centric model for the higher frequencies gives the values 3047 (2943), 2271 (2176) for the symmetrical C−H-oscillations of C_6H_6 and C_6D_6, respectively. These coincide with the experimental values 3060 and 2292, respectively, even considering the error limits.

[6] L. Simons, Soc. Scient. Fenn. Comm. Phys.-Math. **8**, 16 (1935).

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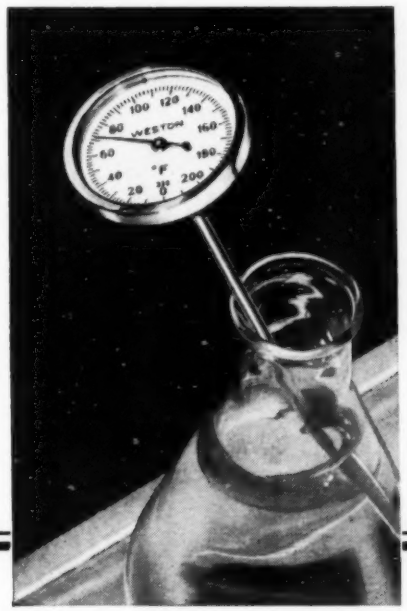

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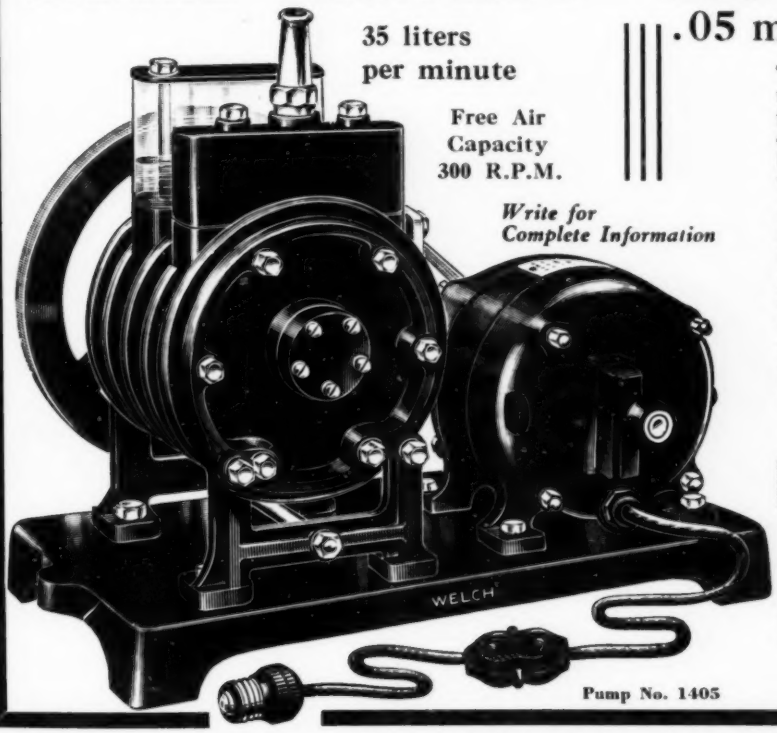

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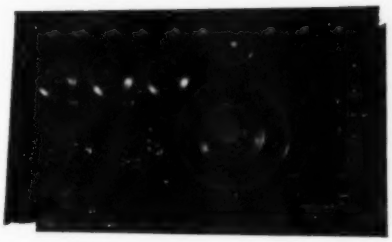

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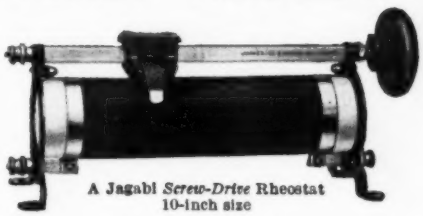

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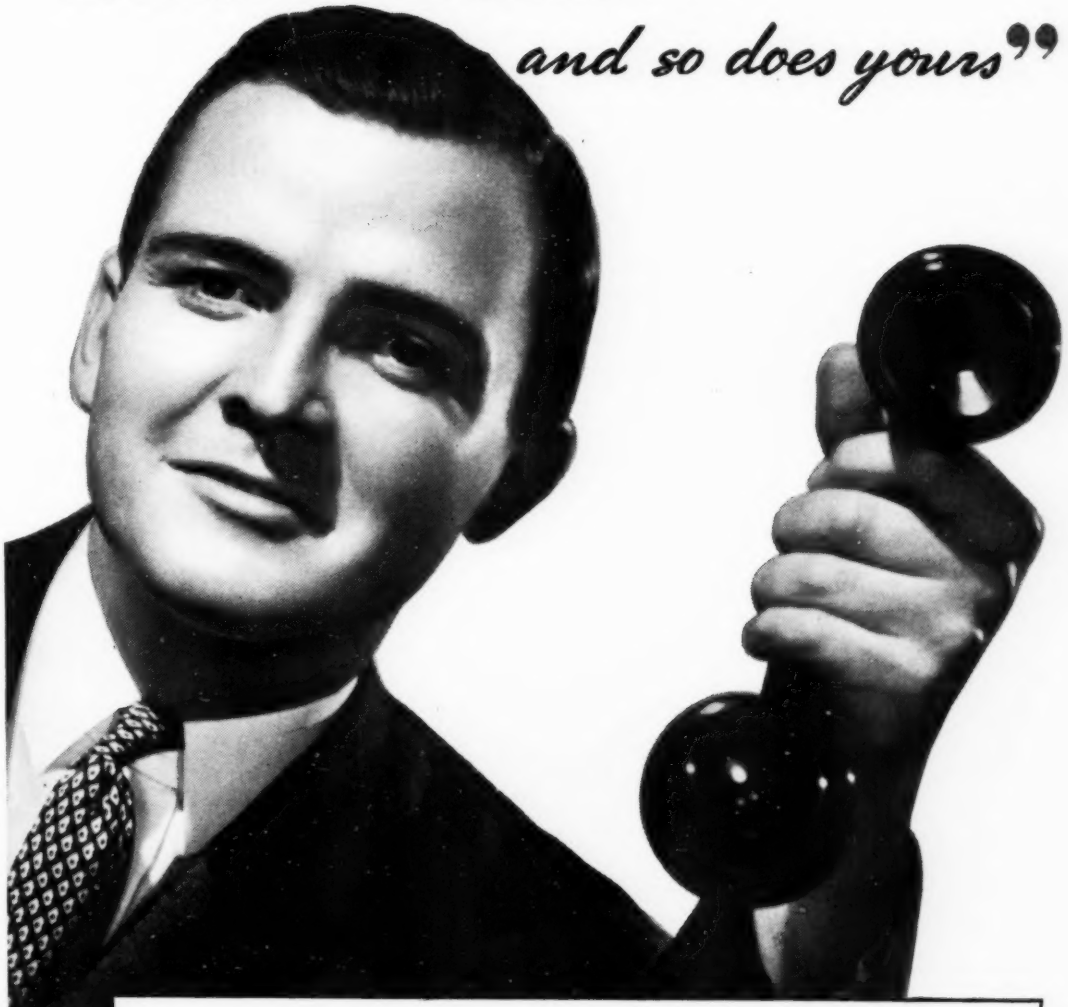

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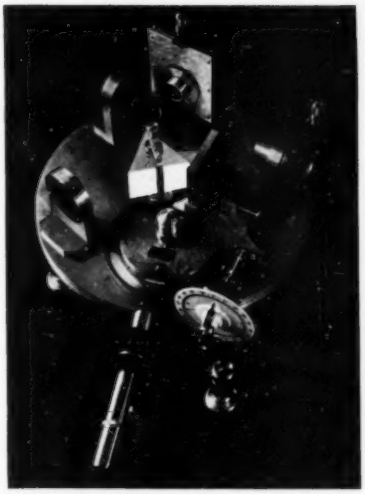

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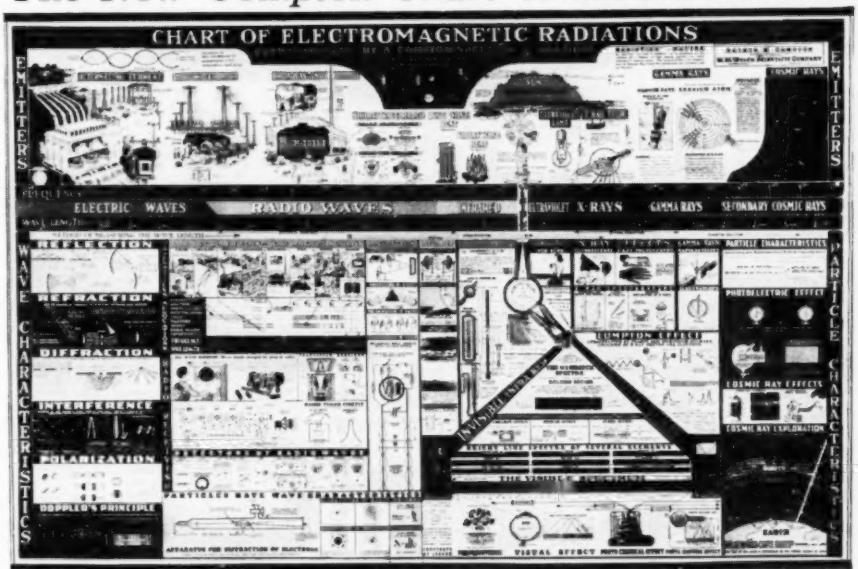

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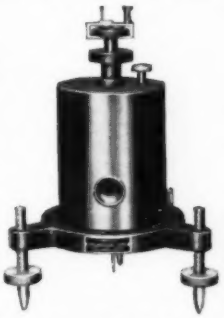

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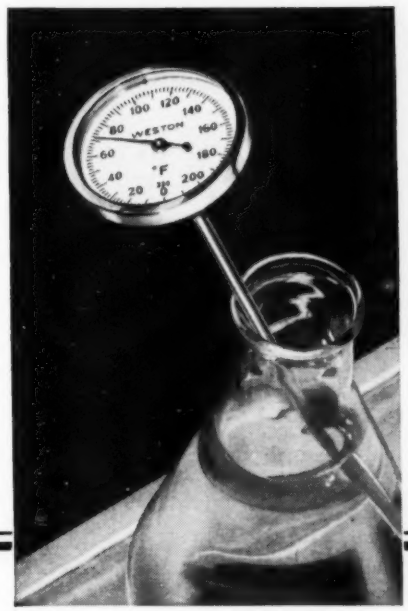

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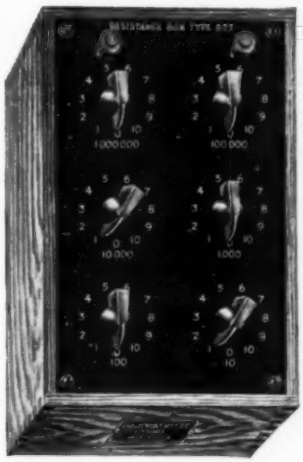

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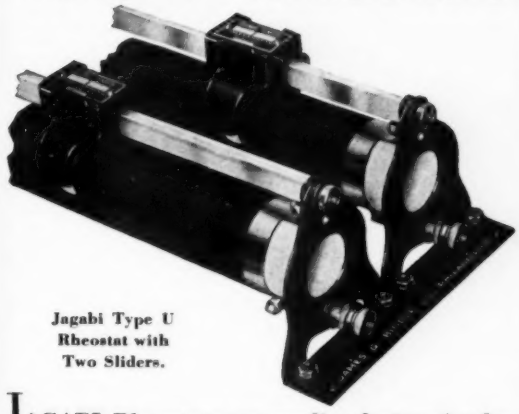

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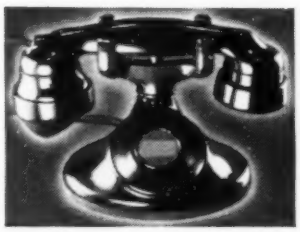

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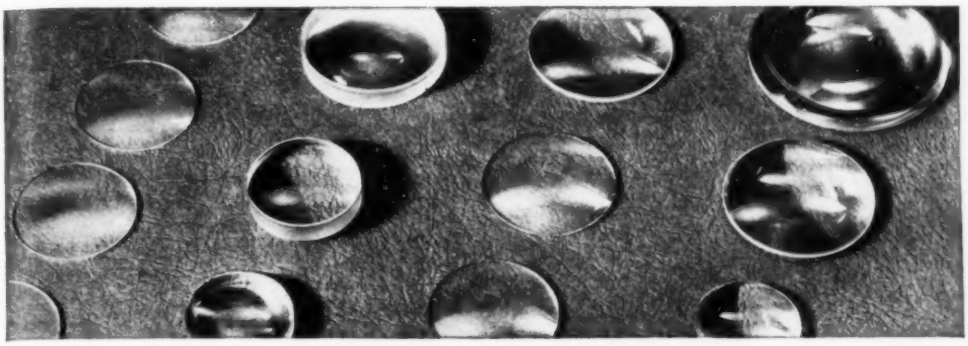

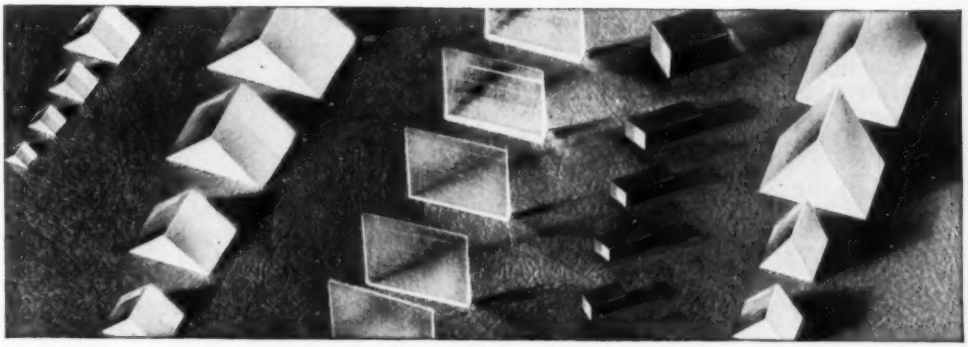

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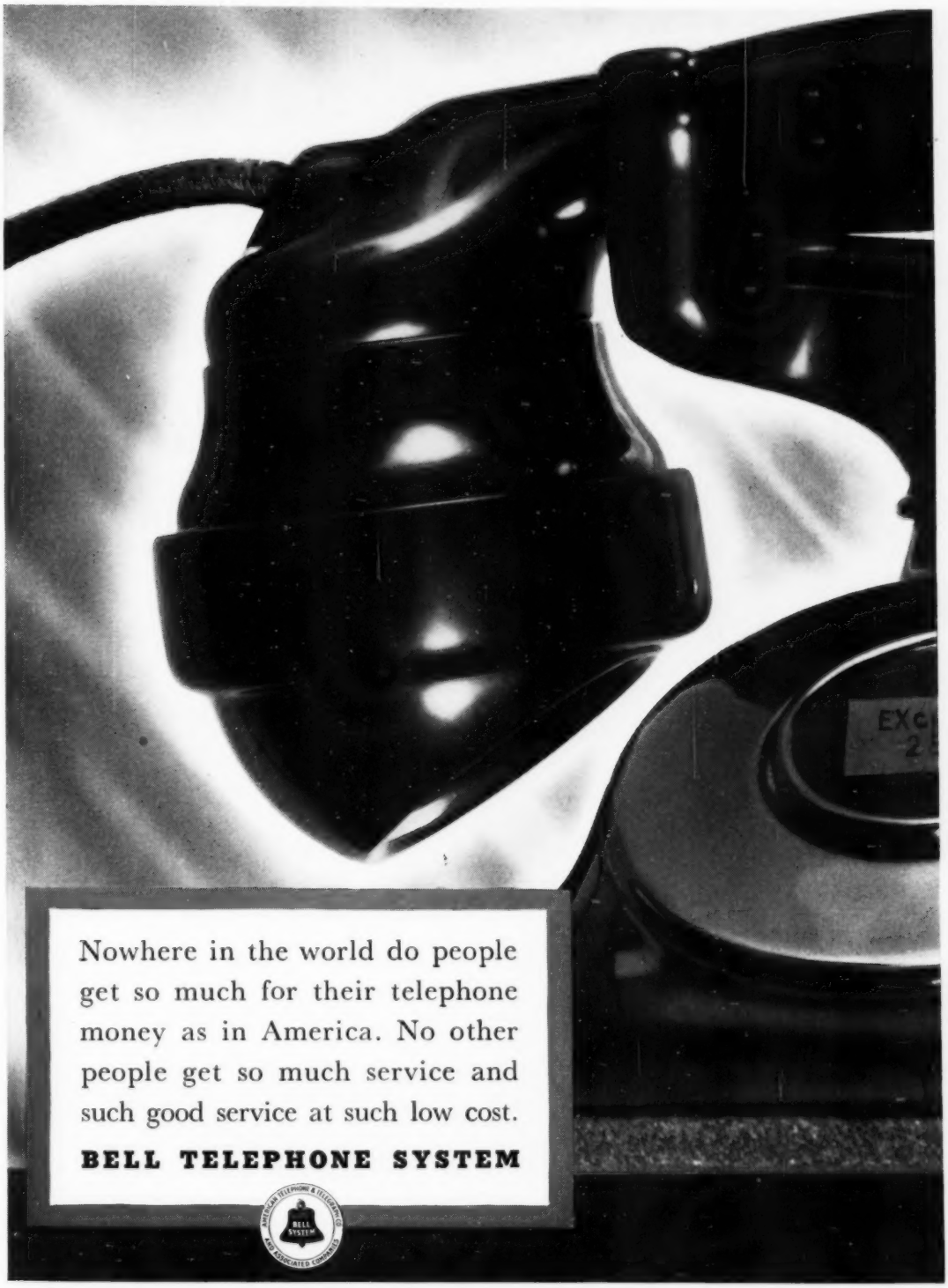
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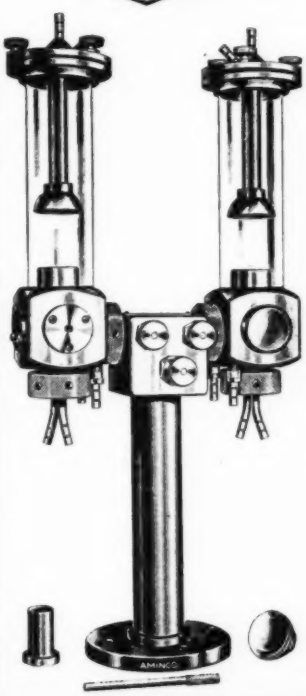

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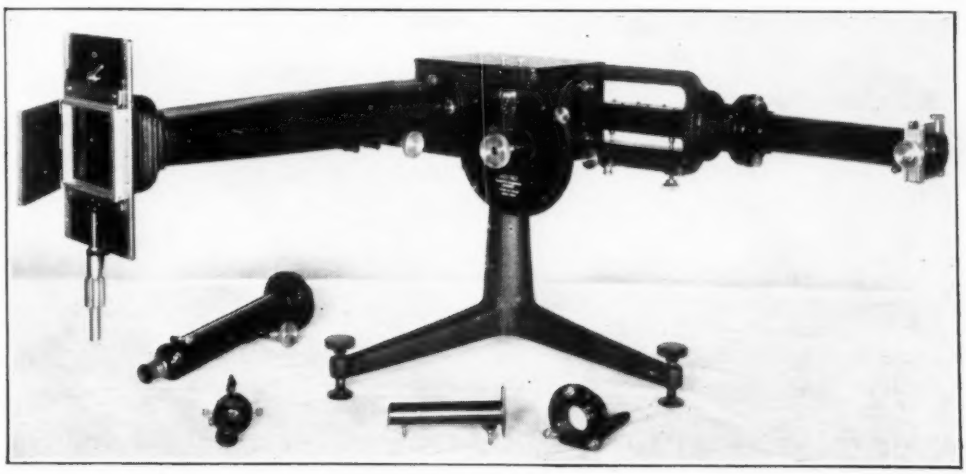

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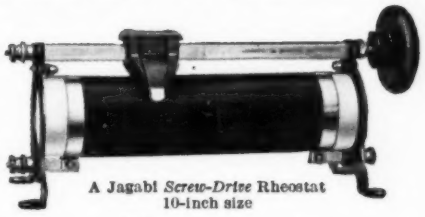

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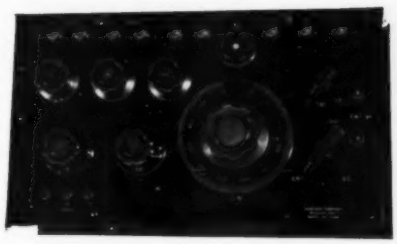

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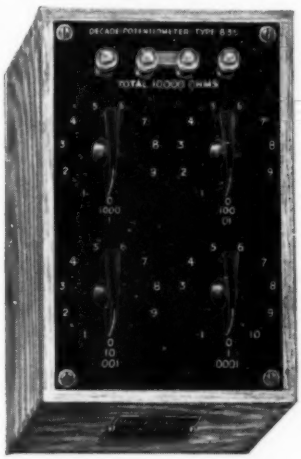

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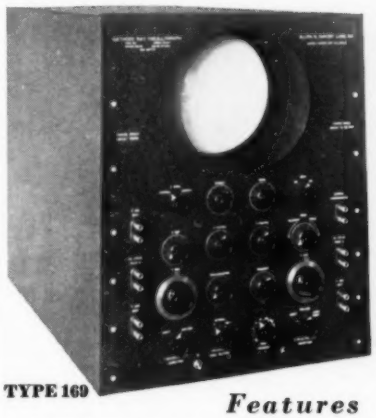

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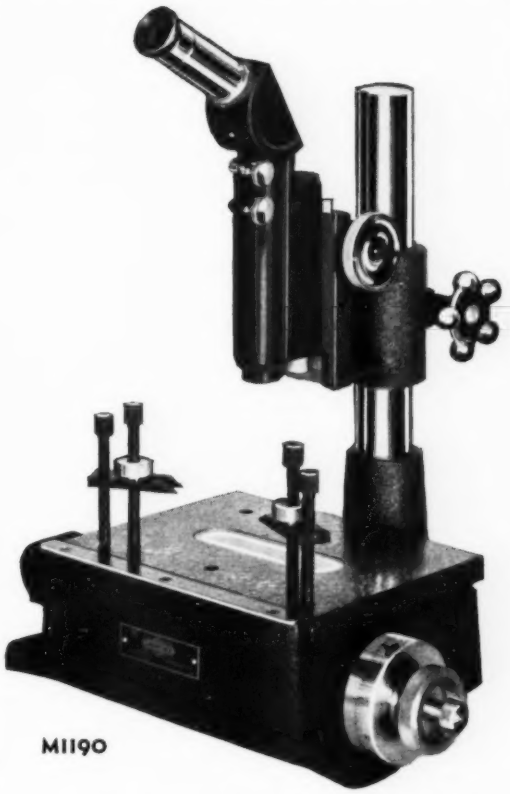

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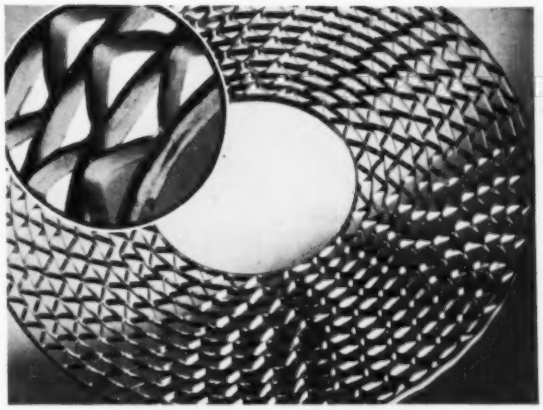

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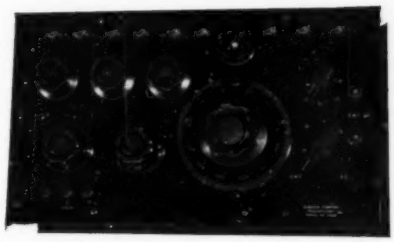

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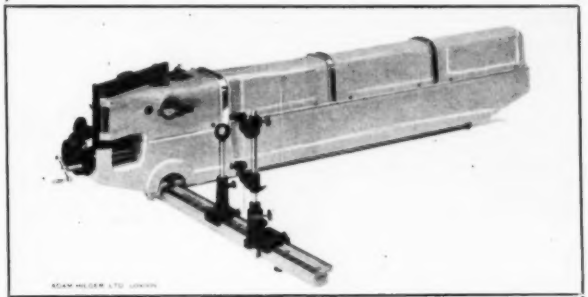

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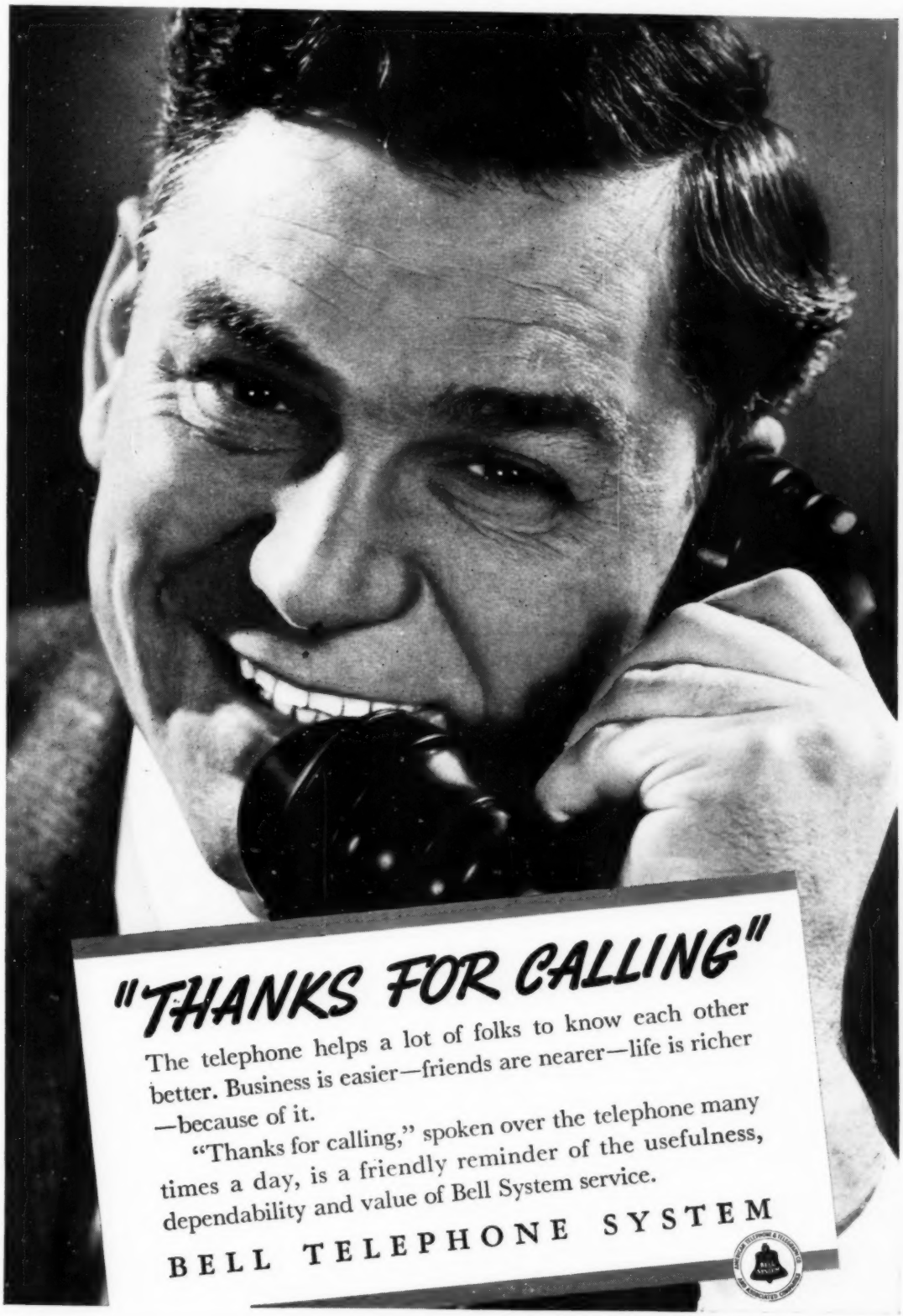
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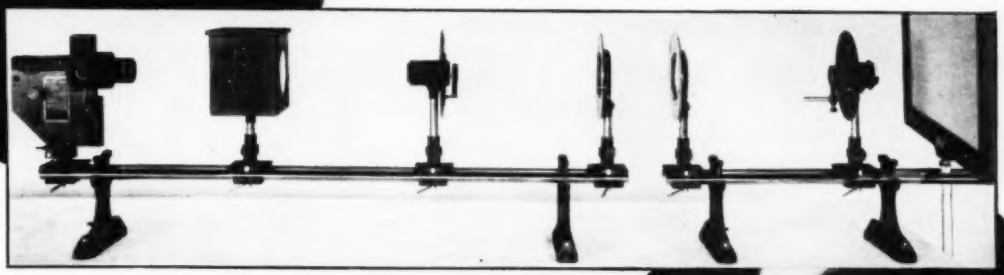

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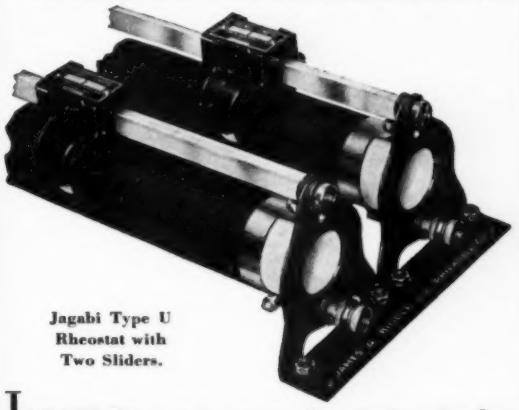

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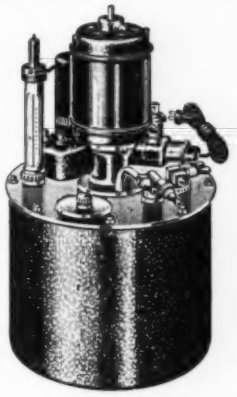

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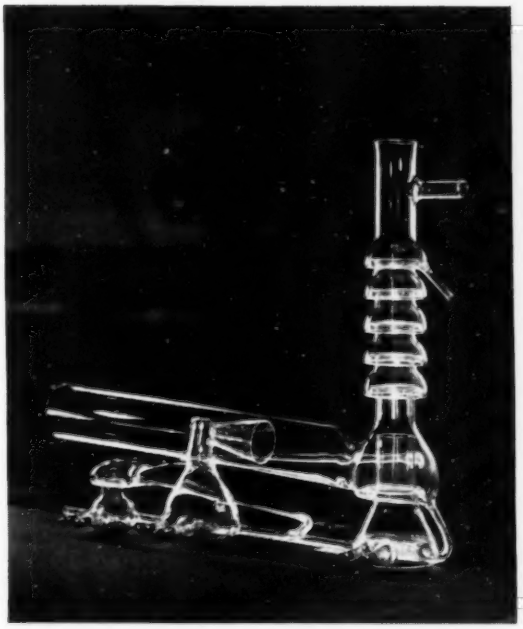

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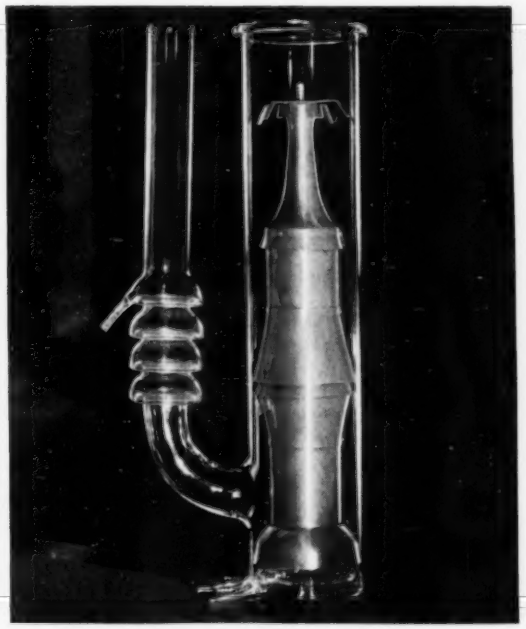

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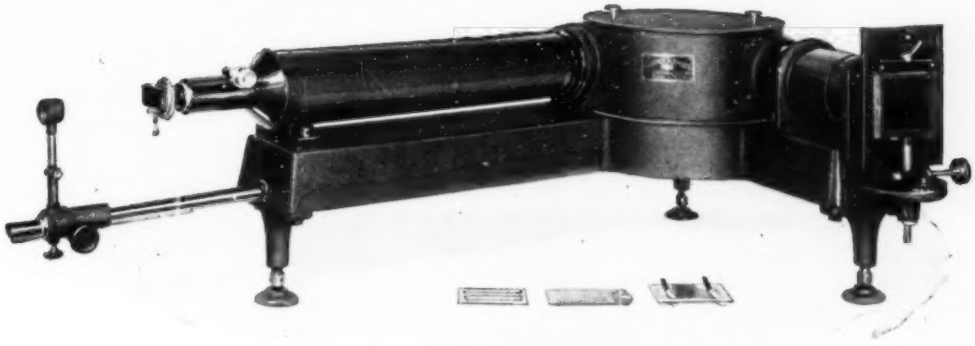

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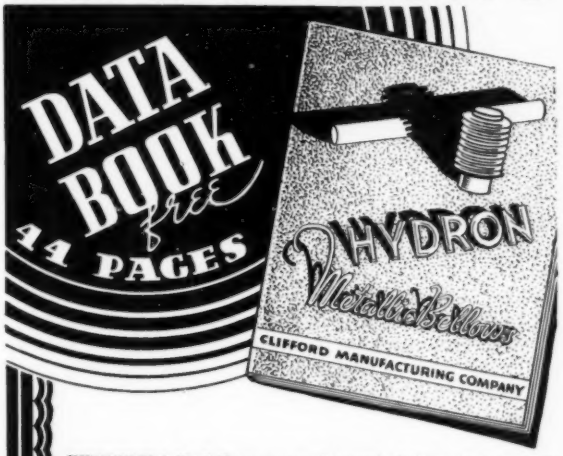

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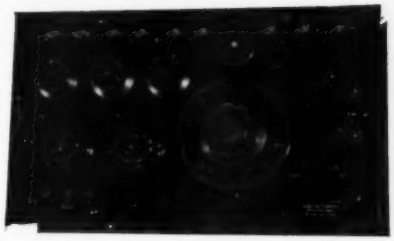

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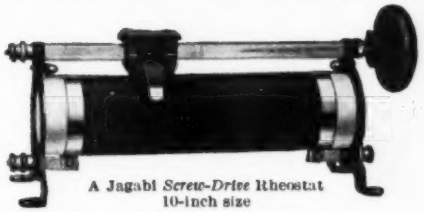

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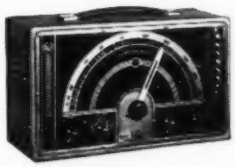

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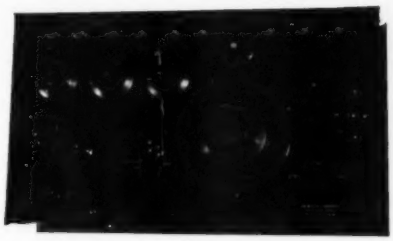

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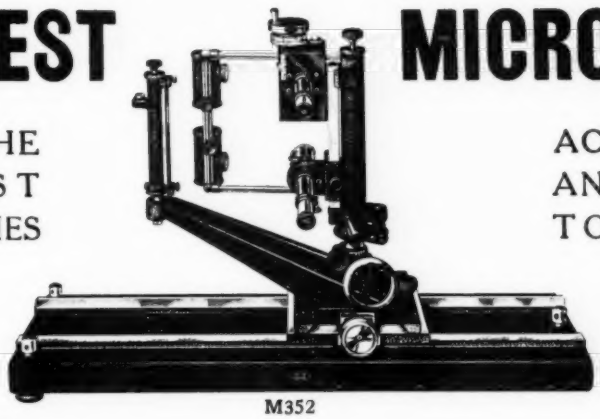

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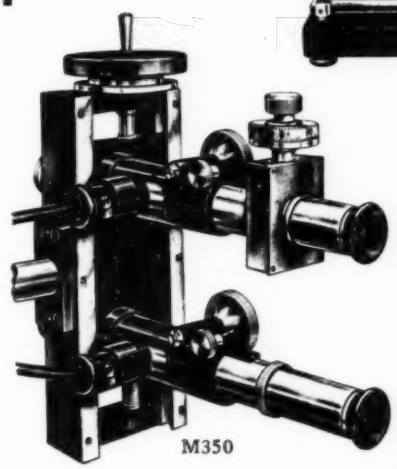

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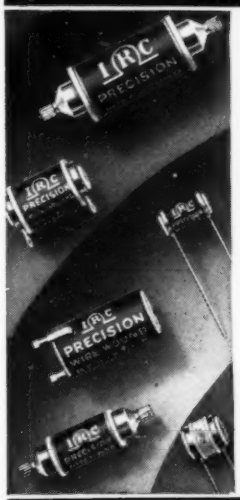

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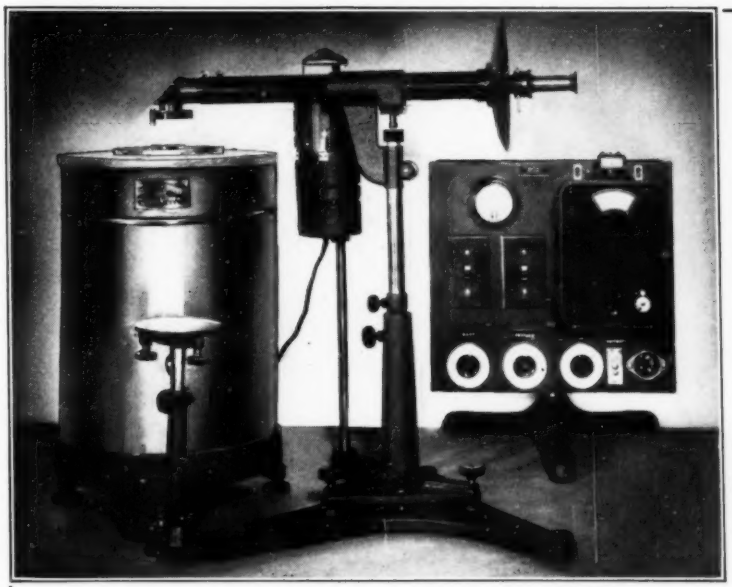

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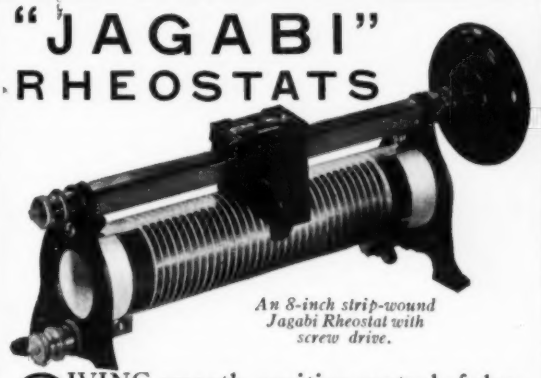

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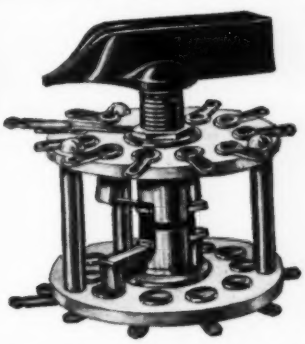

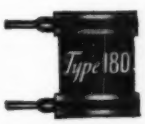

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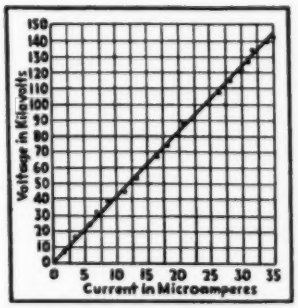

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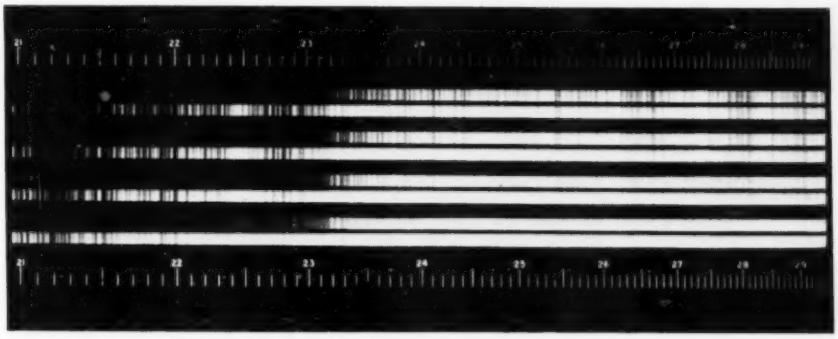

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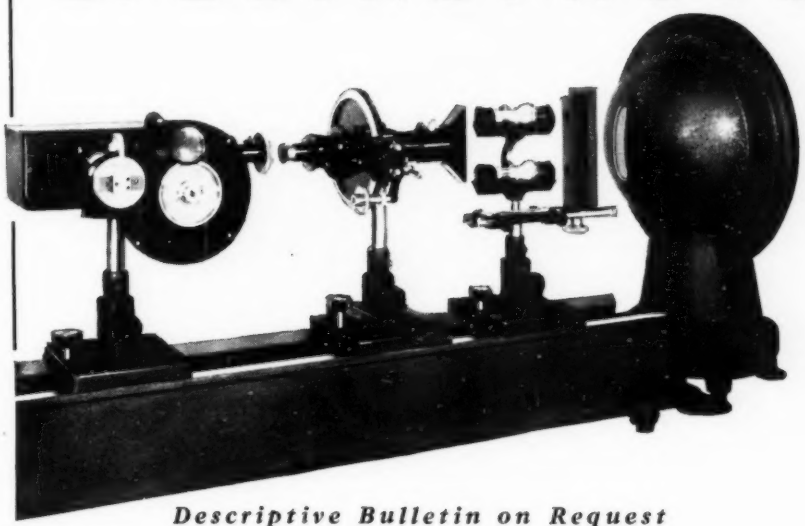

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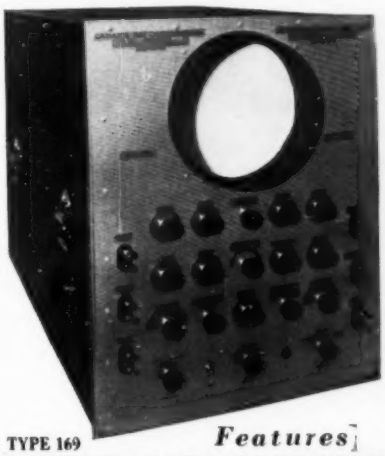

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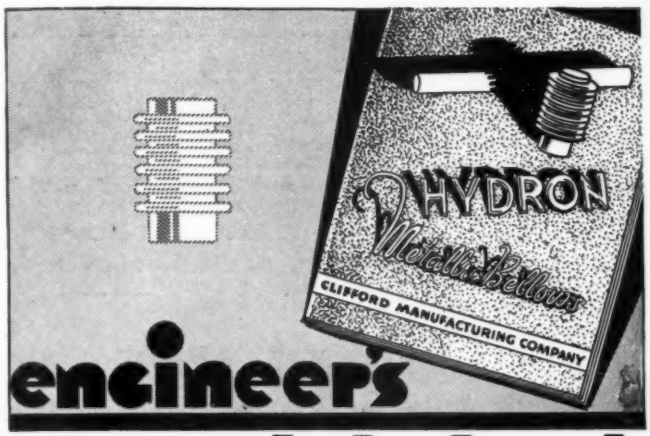

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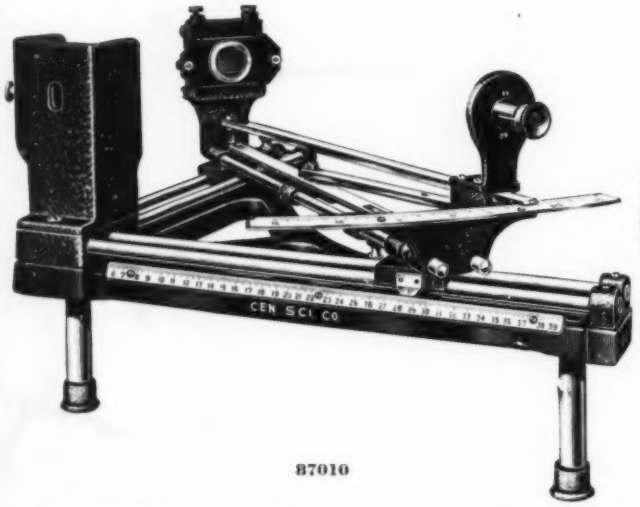

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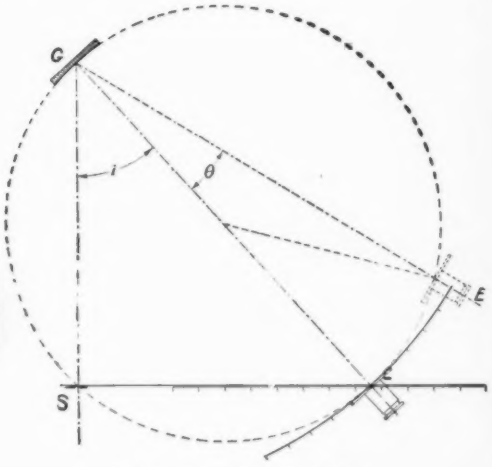

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